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A global–local analytical framework for social-ecological systems: A deductive–inductive approach

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ABSTRACT

Analyzing the complexity of social-ecological systems (SESs) remains an empirical challenge, particularly when analytical frameworks must operate across decision-making scales. Global SESs frameworks are applied locally, but often imperfectly, and local evidence seldom informs their refinement. Here, we integrate global deductive and local inductive approaches to operationalize a cross-scale analytical framework tailored to local decision-making contexts and evaluate its representativeness using indicators available for the Long-Term research at Chamela–Cuixmala SESs in Mexico. Through a deductive approach, we drew on two global frameworks—the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and the Essential Ecosystem Services Variables (EESV)—to identify three initial components: (1) ecological supply of nature's contributions to people (NCP), (2) co-production of NCP, and (3) demand for NCP. Complementing this, an inductive assessment of how 245 indicators have been used across three local decision-making scales (plot, smallholder, and land tenure) revealed two additional components: benefits derived from NCP and SESs management. We found that research to date in Chamela-Cuixmala has predominantly focused on the co-production of NCP (42 % of indicators) and SESs management (21 %). Our results demonstrate that iterating between deductive and inductive approaches strengthens the alignment between local SESs characterization and global sustainability frameworks. The resulting analytical framework is both context-specific and operational across scales, offering a practical tool for improving the understanding of SESs complexity and informing global sustainability debates from grounded local evidence.

1. Introduction

Analyzing the complexity of social-ecological systems (SESs) represents an empirical challenge, requiring analytical integrative frameworks that can be applied across decision-making scales. In the past decades, SESs research has provided multiple frameworks to unpack the complexity of human-nature interactions across different spatial and temporal scales (for a review of SESs frameworks, see [1,2]. Frameworks provide sets of assumptions and concepts with the aim to highlight, in an abstract manner, how a specific reality, system, or phenomenon is understood [1,3]. Usually, frameworks are accompanied by a graphical representation that illustrates each concept and the interactions between them. Therefore, a framework is both a tool to analyze reality and a tool to communicate about this reality [3–5].

SESs frameworks, specifically, aim to guide research by identifying the concepts, variables, and processes that are relevant to explain the complexity of SESs, predicting changes, or delineating management strategies toward sustainability [2]. In doing so, SESs frameworks provide reference lists of variables that can represent the most relevant SESs components and the interactions between them, e.g., [6–9]. Despite these developments, analytical tools that allow the assessment and characterization of SESs complexity are still lacking.

To understand and describe SESs complexity, the majority of SESs frameworks emphasize the benefits that nature provides to people and

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how individuals and societies manage and impact ecosystems, e.g., [6, 10–13]. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), for example, has developed a framework to assess the complexity of SESs at global and regional scales [14]. The framework includes the concept of "Nature's contributions to people" (NCP), which considers the multiple ways by which people relate with, demand, and value nature and its contributions [14–17]. Current developments by IPBES, such as the Plural Values of Nature [18] and the Nature Futures Framework (NFF; [17]; https://www.nature-futuresframework.org/ [19] have engaged with people's diverse and plural values of nature, using three broad values perspectives: Nature for Nature, Nature for Society, and Nature as Culture. The "Nature for Nature" perspective relies on the idea that nature has value for itself, regardless of people (i.e. intrinsic values). The "Nature for Society" perspective relies on the idea that nature matters because of the utilitarian benefits it provides to people (i.e. instrumental values). Instead, the "Nature as Culture" perspective considers humans as an integral part of nature and values the meaningful and reciprocal relationship between people and nature (i.e. relational values [20]). Therefore, these three broad perspectives allow us to understand what values support the demand of different kinds of contributions from nature and what types of benefits are perceived and honored by people [17,20]. In addition, the NCP framework explicitly acknowledges that these contributions are not only derived from nature but also require inputs from humans, a process known as "co-production" of NCP [14,21,22]. Yet, the operationalization of these frameworks (NCP, NFF and plural values of nature) in a comprehensive way remains challenging because the absence of clear variables and indicators for each of the NFF broad perspectives, values of nature, and NCP (and its co-production), but see [23,24].

One challenge is the identification of the minimum set of "essential variables" to be monitored. Essential variables constitute critical measurements for the study, report, and management of a system and its changes [25–28]. For NCP, researchers identified Essential Ecosystem Services Variables (EESVs) [29]. The EESVs framework encompasses six comprehensive classes to characterize the interdependencies between nature and societies across space and time [29]: (1) ecological supply, i.e. the ecosystems' structure and functions that lead to the provision of NCP; (2) anthropogenic contribution, i.e. capitals used by people to enhance the ecological supply and co-produce NCP; (3) demand, i.e. the human desire and need for NCP; (4) use, i.e. the active or passive appropriation of NCP by social actors; (5) instrumental values, i.e. the importance of NCP to people as a means to an end [14]; and (6) relational values, i.e. the importance ascribed to how ecosystems contribute to meaningful interactions between humans and nature and between humans in relation to nature [20]. Yet, to date, these EESVs have not been operationalized to characterize SESs complexity.

Although global SESs frameworks guide local assessments, they often fail to align with local realities and rarely incorporate feedback from local empirical studies. Their limited suitability at local scales stems from mismatches in data availability, scale-specific social–ecological dynamics, and the difficulty of capturing locally important interactions that fall outside the categories defined by global frameworks. Despite recent IPBES efforts, such as the NFF [17] and the typology of Values [18], have incorporated local and Indigenous knowledge into global syntheses, systematic feedback from local SESs studies into global frameworks remains limited. This gap highlights the value of integrative deductive–inductive approaches that draw on global initiatives for conceptual guidance while grounding framework development in robust, locally generated evidence. Indeed, local SESs have received relatively little attention due to persistent challenges in collecting and integrating social and ecological data, and in harmonizing diverse framework components. Developing operational analytical frameworks that mobilize social–ecological information for SESs management is an urgent priority, particularly in vulnerable regions of the Global South [30]. Examining how local SESs have been monitored in different contexts can provide essential insights to refine analytical frameworks, support systematic and comparable assessments of SESs characterization, and strengthen management decisions across scales.

The main goal of this study is to operationalize a cross-scale analytical framework that uses nature's contributions to people (NCP) as an entry point to characterize SESs at local decision-making scales through an integrated deductive–inductive approach. First, drawing on two global initiatives—IPBES and the Essential Ecosystem Services Variables (EESV)—we deductively develop an analytical framework that can be applied across multiple decision-making scales. Second, through an inductive approach, we assess the framework's representativeness by examining how existing NCP indicators have been used within the Chamela–Cuixmala Long-Term Social–Ecological Research (LTSER) platform in Mexico. LTSER platforms are coordinated networks for long-term social–ecological monitoring [31]; they offer ideal settings to operationalize global SESs frameworks in local contexts and are especially valuable for advancing place-based research in understudied regions of the Global South [31–34]. Finally, we evaluate the applicability of our cross-scale framework in the Chamela–Cuixmala SESs by analyzing how indicators corresponding to each framework component have been used in the scientific literature.

2. Methods

We built an analytical and cross-scale framework through an iteration of global deductive and local inductive approaches. From a deductive approach, we selected a first set of framework components from the global IPBES and EESVs frameworks. Then, from an inductive approach, we operationalized the framework at three decision making scales and assessed the representativeness of its components by reviewing the NCP indicators used in the literature for the Chamela-Cuixmala region.

2.1. Development of the framework

First, an analytical framework was built deductively upon the global IPBES and ESSVs frameworks (Fig. 1). From the IPBES framework [14], we focused on the interactions across its six main elements: 1) nature, 2) NCP, 3) anthropogenic capitals and assets, 4) institutions and governance systems, and other indirect drivers of change, 5) direct drivers of change and, 6) good quality of life. From the EESV framework [29], we incorporated three classes: 1) ecological supply, 2) co-production, and 3) demand (encompassing use and values) of NCP. These three classes articulated the interactions across the key elements of the IPBES framework. Second, from an inductive approach, we assessed the representativeness of this analytical framework based on NCP indicators used in the Chamela-Cuixmala region in Mexico (see section "Assessing the representativeness of the cross-scale analytical framework" below). After this assessment, we also included the benefits from NCP and SESs management as additional framework components (Fig. 1), leading to a final set of five components: (1) *ecological supply*, (2) *co-production of NCP,* (3) *management, (4) demand*, and (5) *benefits from NCP*. Additionally, for each component, we defined a set of subcomponents that guide the characterization and description of SESs complexity (Table 1, Appendix D) and examined how indicators for the framework components and subcomponents have been used in the scientific literature for the Chamela-Cuixmala SES.

2.2. Case study

The Long-Term Social-Ecological Research site Chamela-Cuixmala region is a biodiversity hotspot located in the state of Jalisco, Mexico. Ecologically, the region is mainly composed of a mosaic of tropical dry forests and grassland patches, but also of other ecosystems such as mangroves and wetlands. The outstanding biodiversity and the need to preserve it from land transformation led to the declaration of the central part of this region as the Chamela-Cuixmala Biosphere Reserve in 1993

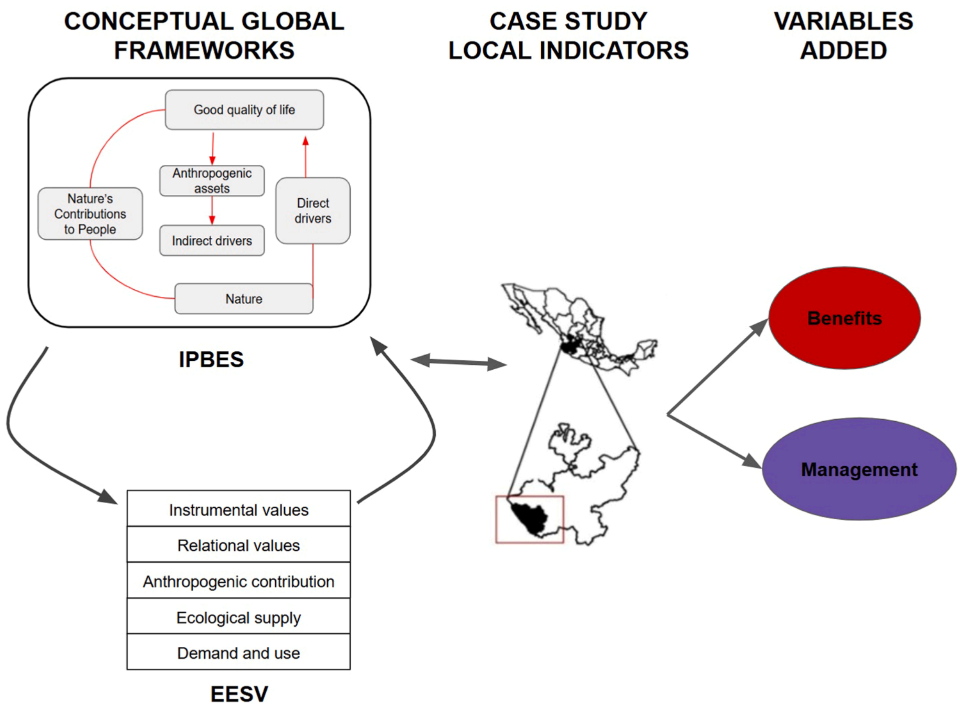

Fig. 1. Development of the analytical framework. The figure integrates the conceptual global frameworks of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES; Díaz et al. 2018) and the Essential Ecosystem Services Variables (EESV, Balvanera et al. 2022). EESV were used to analyze the interactions among IPBES elements emphasized in the image by the red arrows. Following a literature review from the case study area (Chamela-Cuixmala, Mexico) and an indicator assessment, two additional variables—Benefits and Management—were integrated into the proposed framework to better reflect local complexity and values associated with Nature's Contributions to People (NCP).

Table 1
Framework's components description, its subcomponents and guiding questions for characterizing Social-Ecological Systems (SESs) through Nature's Contributions to People (NCP).

Component	Description	Subcomponents	Guiding question for characterizing SESs through NCP	References
Ecological supply	Elements from nature that underline the potential capacity of ecosystems to provide NCP	Structure Species Function	What nature's elements contribute to the delivery of specific NCP?	Balvanera et al. (2022) Pereira et al. (2013)
Co-production	Process in which humans invest to enhance ecological supply and to make use of NCP	Social capital Human capital Manufactured capital Financial capital	Which anthropogenic capitals take part in the process of generating and delivery of specific NCP?	Balvanera et al. (2022) Palomo et al. (2016) Isaac et al. (2022)
Management	Decisions that contribute to increase or decrease the supply of a desired NCP	Time Intensity Extension	What decisions in the land modify ecosystem conditions to increase the supply of desired NCP?	Van Oudenhoven et al. (2012) Trilleras et al. (2015) Zermeño-Hernández et al. (2015) Pérez-Cárdenas et al. (2021)
Demand (use and values)	Human desire or need for an NCP and, therefore, it encompasses dimensions of use and value. While use refers to an active or passive appropriation of a NCP, values are the importance that societies or individuals give to specific NCP. We consider only values describing meaningful interactions between humans and nature.	Priorities of use Instrumental values Relational values	How values can shape the co-production of specific NCP in order to achieve good quality of life?	Balvanera et al. (2022) Chan et al. (2016) Pascual et al. (2017) Arias-Arévalo et al. (2017)
Benefits	Elements that contribute the most to having a good quality of life	Good social relationships Good health Livelihood security Energy security Food security Water security	Which are the key benefits from specific NCP that contribute the most to people's quality of life?	MA (2005) IPBES (2018 ECA report)

(see Fig. 2).

The ownership regime is crucial for land management strategies in the Chamela-Cuixmala region [35]. Surrounding the Biosphere Reserve, there are 11 *ejidos*, i.e., land tenure units of tracts of land held in common by the inhabitants of a Mexican village and farmed cooperatively or individually. The *ejido* was conceived as a hereditary but unalienable semi-collective form of land tenure; these properties technically belonged to the federal government but were given to peasants between 1950-1975 as a result of the Agrarian Land Reform aimed to colonize the coasts of the country [36,37]. Each *ejido* member, called *ejidatario* (smallholder, peasant), had rights on the communal land allotted for the use of all registered families within the *ejido* through the *ejidal plot* (i.e. a portion of land where individual or communal decisions are made). In the Chamela-Cuixmala region, most of the tropical dry forests outside

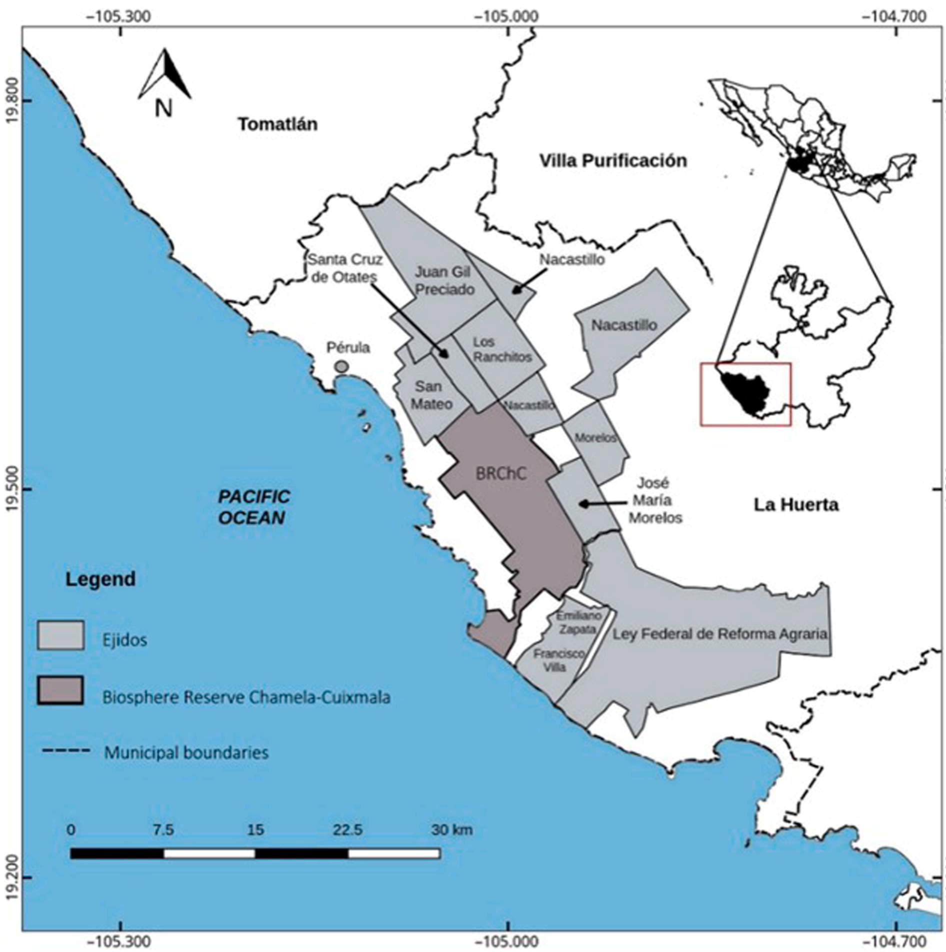

Fig. 2. Location of the Chamela-Cuixmala region, comprised of the Chamela-Cuixmala Biosphere Reserve (BRChC) and the surrounding *ejidos,* in the state of Jalisco, Mexico (Modified from Castillo et al. 2018).

the Biosphere Reserve (ca. 70-80 %) are under the *ejido* tenure form [38, 39].

The Chamela-Cuixmala Biosphere Reserve has belonged to the International Long-Term Ecological Research Network as a Long-Term Social-Ecological Research site since 1971. This nomination has fostered the study of the region from a transdisciplinary social-ecological perspective, particularly throughout the ecosystem service framework, e.g., [40–42]. Such research has promoted that this region became one of the most studied tropical dry forest sites in the Neotropics [41,43], being an excellent case study for the operationalization of our framework.

2.3. Framework operationalization

To facilitate the operationalization and environmental decisions and policy-making of the proposed framework, we first identified three relevant local decision-making scales – i.e., individual plots, smallholders, and land tenures, similar to Klaus et al. [44]. Second, focusing on NCP as the key articulating element of the IPBES framework, we selected the most relevant NCP for the Chamela-Cuixmala region based on a universally applicable set of 18 categories that can be identified in a sharp, organized, and self-consistent system (i.e. the generalizing IPBES perspective, [15]). Third, based on the Chamela-Cuixmala SESs literature, we identified NCP based on local knowledge systems that might not be universally applicable (i.e. the context-specific IPBES perspective [15]), and related them to the generalizing categories. The final set of general NCP considered for operationalizing the proposed framework comprised eight NCP: (1) habitat creation and maintenance, (2) regulation of climate, (3) regulation of freshwater quantity location and timing, (4) formation protection and decontamination of soils and sediments, (5) food and feed, (6) materials, companionship, and labor, (7) learning and inspiration, and (8) supporting identities. Finally, we identified exemplary indicators available in the Chamela-Cuixmala region to describe these NCP across the different local decision-making scales, components, and subcomponents of our analytical framework.

2.4. Assessing the representativeness of the cross-scale analytical framework

To assess the extent to which NCP can be monitored across local decision-making scales, we identified readily available indicators for the Chamela-Cuixmala region. We collected all available social-ecological indicators by performing a systematic review of the scientific and gray literature studying NCP in the Chamela-Cuixmala region for the period 2008-2019. We considered two literature repositories to conduct the literature review. First, for the literature published between 2008 and 2016, we used the documentary database of the Chamela-Cuixmala Biosphere Reserve (2008-2016). Second, for the literature published in the period 2016-2019, we used the repository of the Universidad Nacional Autónoma de México (tesiunam.dgb.unam.mx), Google Scholar, Web of Science, Redalyc, the repository of the Universidad Michoacana (bibliotecavirtual.dgb.umich.mx/) and the repository of the Universidad de Guadalajara (https://riudg.udg.mx/). The search string to conduct the literature review included key terms in Spanish and English referring to the region (e.g., “Jalisco AND Chamela”, “Chamela”), to its main ecosystem (“Tropical Dry Forest”), to NCP (e.g. “ecosystem service") and to "management". For the complete search string, view Appendix A.

This search yielded 472 theses (251 B.Sc., 154 M.Sc., 67 Ph.D.) and 673 scientific articles. We screened these documents to keep only those that empirically explored NCP in the Biosphere Reserve surroundings, where people and nature interact directly. We obtained a final set of 15 scientific papers and 15 theses (Appendix B).

From each document, we extracted all social and ecological indicators used to characterize and describe the five components identified in the analytical framework (ecological supply, co-production of NCP, management, demand, and benefits from NCP), leading to a final set of 881 indicators. Then, we selected those indicators that were frequently used across space (i.e., used in at least five tenure units) and time (i.e., used for at least five years). For the case of social and management indicators, the time aspect was excluded due to the lack of long-term empirical social research in the region. After the selection by space and time, we merged redundant indicators when they measured the same component. We obtained a final set of 245 indicators (Appendix C). Finally, we classified each indicator into the different components and subcomponents of our framework and identified the decision-making scale in which they were used.

3. Results

3.1. Analytical framework to study SESs through NCP

Our iterative deductive/global-inductive/local explorations informed the identification of five social-ecological components, namely *ecological supply, co-production, management, demand* (encompassing *use and values*), and *benefits from NCP*, that articulate the interactions across key elements of the IPBES framework (Fig. 3). These five components have been identified as cross-cutting variables to analyze SESs complexity. For each component, we identified relevant subcomponents that refer to different social-ecological attributes and processes (Table 1; for a detailed explanation of the subcomponents, see Appendix D). To enable the identification of variables that can characterize and describe the different subcomponents, we consider a set of guiding questions (Table 1).

Although these components represent different conceptual notions, they can overlap and interact in complex ways (Fig. 3; interactions between components are indicated by arrows). For example, the sense of achievement of a good quality of life directly depends on how the NCP *demands* are satisfied, how NCP *benefits* are appropriated (*use),* and what is considered important for fulfilling a life that it is worthy to live (*values*). For example, in the Chamela-Cuixmala region, people's sense of a good quality of life depends on the common identity built around cattle and, therewith, on the relational value of cultural identity [39].

At the center of the framework, we placed the component of *NCP co-production* since it often modulates the supply of NCP, how people benefit from and demand NCP as well as how people manage NCP (Fig. 3). For instance, *the ecological supply* of fodder by the *Acacia sp.* "Huizache" in the Chamela-Cuixmala region is only possible through the knowledge of which species to keep and how to grow them (i.e., human capital from co-production) and the machinery used to cut down trees

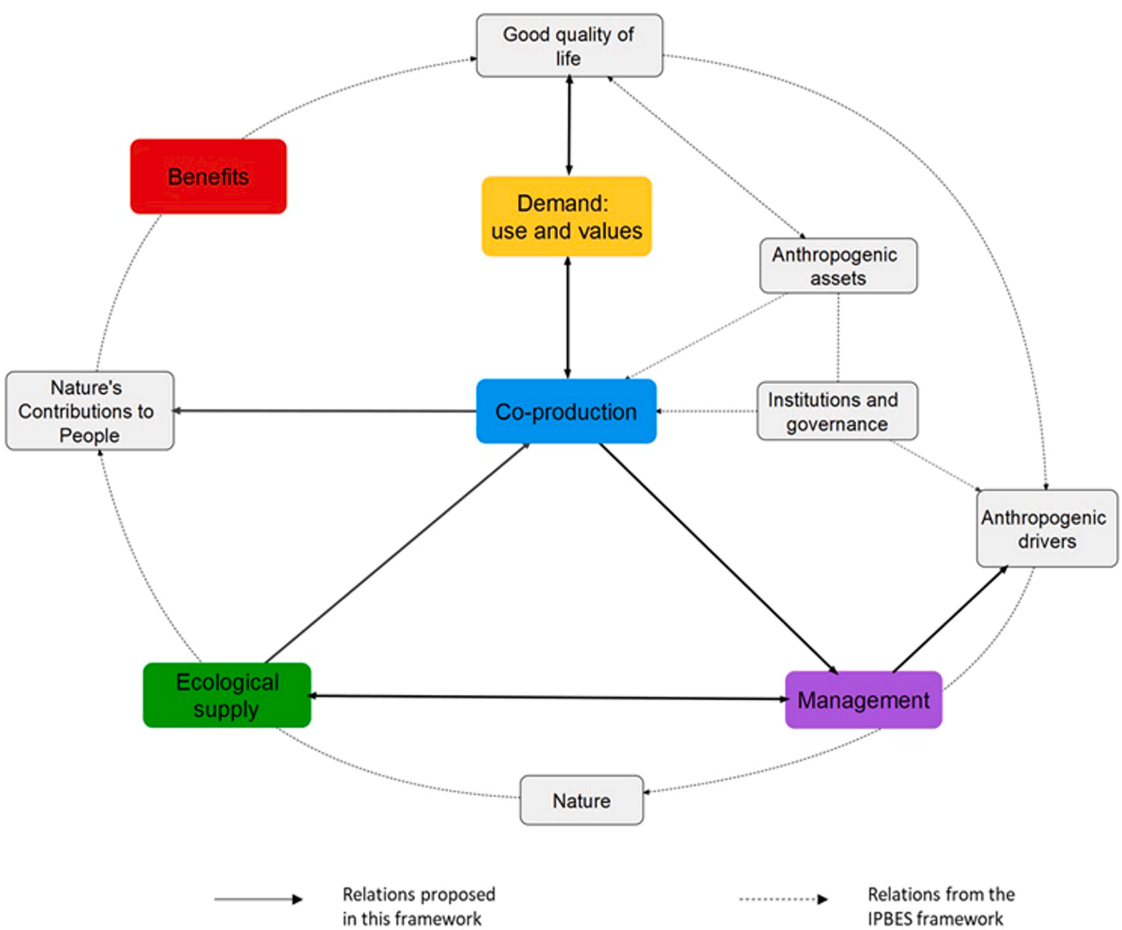

Fig. 3. Analytical framework incorporating five social-ecological components across the interactions among the elements of IPBES framework that drive the characterization of SES: *ecological supply, co-production, management, demand* (encompassing *use and values*), and, *benefits from Nature's Contributions to People*. The five components, in colors, represent the flows of material, decisions, and values around NCP within a SES. Grey boxes represent IPBES's original elements. Dotted arrows represent IPBES's original linkages. Black arrows represent new interactions proposed in this framework.

(manufactured capital) [45]. The intensity by which a smallholder uses the machinery to benefit from fodder defines the management strategy and, therefore, *co-production* also affects *ecological supply* through *management. Co-production of NCP* also affects how people *benefit from NCP*. For example, those people who received remittances (financial capital) are more likely to construct facilities to store and save water, leading to water security (i.e. *benefits from NCP*) [46]. Moreover, *co-production* might be also affected by the *demand: use priorities and values.* For example, the value systems of smallholders in the Chamela-Cuixmala region determine how much financial capital is invested in bovine production: when farmers' value systems are dominated by instrumental values, they invest a higher amount of money (financial capital) to gain greater financial benefits [47]. The way co-production is modulated by the *demand* and by governance leads to different *management* (Fig. 3). For example, in the Chamela-Cuixmala region, management decisions such as the number of cattle introduced in a pasture, are modulated, among other reasons, by the subsidies promoted by, for example, “Livestock Productivity Stimulus Program (Programa de Estímulos a la Productividad Ganadera, PROGAN)” [48,39].

Table 2
Exemplary operationalization of the analytical framework and decision-making scales in which the given indicator has been used to analyze and characterize NCP in the Chamela-Cuixmala SES. Complete references are provided in Appendix B. IP= Individual plot, SH= Smallholder, LT= Land tenure.

				Components and subcomponents of the analytical framework																				
				Ecological supply			Co-production				Benefits						Demand: use and values				Management			
NCP generalizing perspective	Context-specific NCP	Indicator	Units	Ecosystem structure	Ecosystem function	Species population	Human capital	Social capital	Financial capital	Manufactured capital	Good social relationships	Good health	Livelihood security	Energy security	Food security	Water security	Values	Instrumental values	Relational values	Priorities of use	Time	Intensity	Extension	Reference
NCP1. Habitat creation and maintenance	Pasture availability	Richness of herbaceous vegetation	rarefaction of observed herbaceous *spp*		IP																			22
NCP1. Habitat creation and maintenance	Types of ecosystems	Land use cover	% or ha	IP, LT																				21
NCP4. Regulation of climate	Economic valuation of climate regulation	Economic valuation carbon stock	USD ha^{-1}														SH	SH						12
NCP4. Regulation of climate	Shade for livestock	Carbon stock	T ha^{-1}		IP																			14
NCP6. Regulation of freshwater quantity, location and timing	Water availability	Access to water	Number of wells per cover type					IP, SH					IP, SH			IP, SH								13
NCP8. Formation, protection and decontamination of soils and sediments	Soil erosion prevention	Elevation	m	IP, LT																				30
NCP12. Food and feed	Use of forest	Edible products harvested	kg extracted per cover type	SH			SH						SH		SH									13
NCP12. Food and feed	Use of exotic species	Fodder species	*spp*				SH		SH															13
NCP12. Food and feed	Pasture for livestock	Biomass fodder plants	t ha^{-1}	IP																				25
NCP13. Materials, companionship and labor	Access to the land	Distance to the road	km					IP																7
NCP13. Materials, companionship and labor	Fodder production capacity	Planted pasture surface	ha				IP, SH, LT		IP, SH, LT														IP, SH, LT	5
NCP13. Materials, companionship and labor	Production capacity	Number of owned plots per *ejidatario*	count						SH				SH											13
NCP15. Learning and inspiration	Connection with the forest	Number of useful tree species identified per *ejidatario*	count	SH		SH	SH						SH							SH				28
NCP17. Supporting identities	Connection with the landscape	Sense of identity	Relative importance per cover type														SH		SH					13

Captions. Santillán Carvantes et al.

3.2. Operationalization of the analytical framework across local decision-making scales

Our proposed framework focuses on identifying opportunities for action at local decision-making scales through NCP characterization and description. In total, we identified 14 context-specific NCP for the Chamela-Cuixmala region, which were related back to eight generalizing NCP categories (Table 2). For each NCP, we also identified a set of exemplary indicators that were widely used at different decision-making scales in the Chamela-Cuixmala region to characterize and describe each component and subcomponent (Table 2). Three decision-making scales were considered to operationalize the framework: individual plots, smallholders, and land tenure units.

Individual plots refer to the parcels of land owned by the smallholders, being the finest spatial decision-making scale. Many ecological studies collect and analyze their data using individual plots as the unit of analysis [44,49,50]. For example, in the Chamela-Cuixmala region, soil research has largely been conducted at this scale evidencing the effect of deforestation and burnings on soil fertility [51,52].

Smallholders refer to the plot owners who have land tenure rights and take decisions on their land. Smallholders are often considered key actors in many long-term social-ecological research sites, since their management decisions have a direct impact on the land [31]. For example, in the Chamela-Cuixmala region, smallholders' information needs have been identified to manage the land [41].

Land tenure units refer to the minimum governance unit where either legal or communal informal decisions take place. Within a land tenure unit, different individual plots may be contained. This scale is particularly relevant when connecting institutions and ecosystems, since this unit is often the one at which census data is the finest and publicly available [53]. For example, in the Chamela-Cuixmala region, the federal government launched the program PROCEDE (Program for Certification of *Ejido* Rights and Titling of Urban Plots) which allowed the privatization of an *ejido* [48]. Privatization of *ejidos* fragmented smallholder communities, which led to weakening *ejido* institutions and local governance [37,48]. However, depending on the *ejido* and its self-organization the impact of that reform has had a greater or lower impact on forest management and collective action management [48,54].

3.3. Framework representativeness in our empirical case study

The assessment of the framework through analyzing the existing scientific literature of the Chamela-Cuixmala region shows the paramount importance of *co-production* since 42 % of the indicators used referred to this component (Fig. 4). Twenty-one percent of indicators referred to *management* and 18 % to *ecological supply* (Fig. 4). These three components, out of the five that make up this framework, covered 81 % of indicators used in the region to characterize and describe SESs (Fig. 4).

The operationalization of this framework for the Chamela-Cuixmala region allowed the identification of indicators that have been used to characterize the five components and their subcomponents across the three decision-making scales (Table 2). Overall, we found a connection between the indicators used to describe each component and the scale at which the data is available (Fig. 4). While *ecological supply* was largely assessed by using indicators measured at the individual plot scale (64 % of indicators); *demand* and *benefits* from NCP were largely monitored at the *smallholder* scale (68 % and 58 %, respectively). For example, to characterize the regulating NCP of habitat creation and maintenance, many studies used the indicator 'richness of herbaceous vegetation' (i.e. *ecological supply*) that was measured at the *individual plot* scale. For characterizing the NCP of regulation of climate, some studies used the indicator "Economic valuation of carbon stock" (USD ha-1, i.e. *demand*)

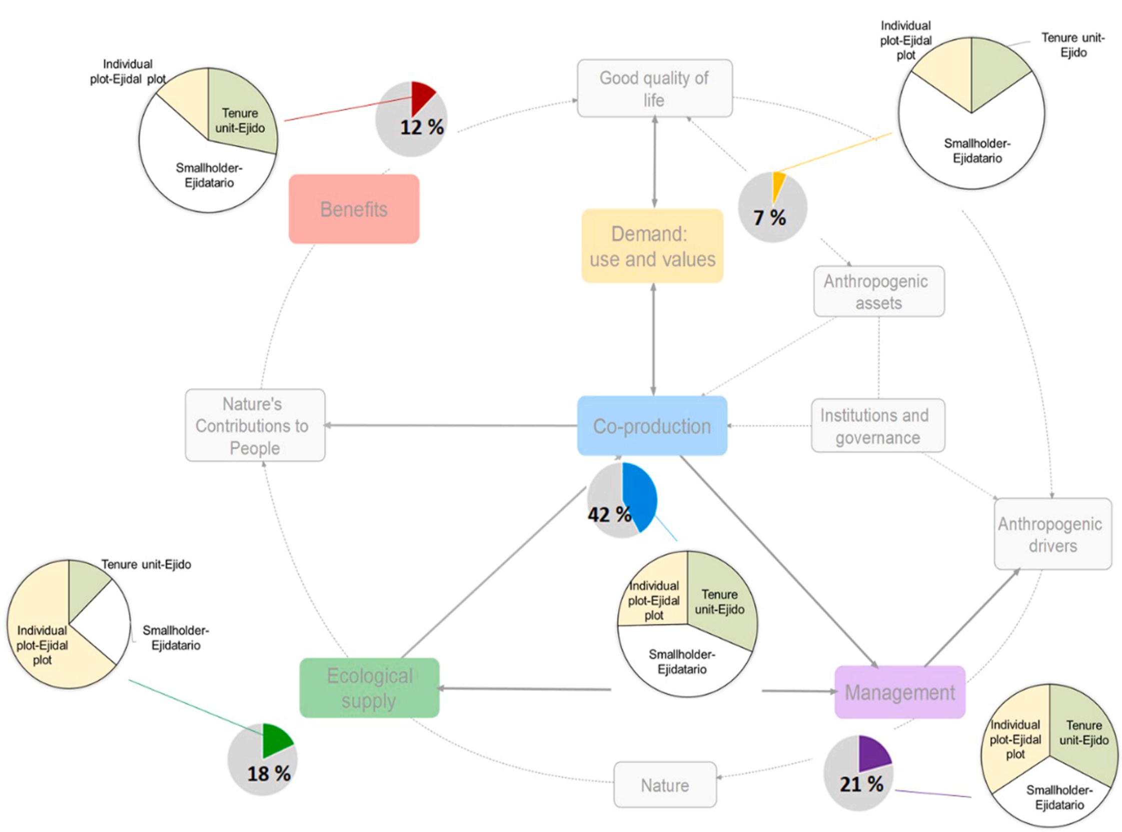

Fig. 4. Percentage of indicators per social-ecological component. Bigger pie charts indicate their percentages per local scale: individual plots, smallholders, and land tenure units. Note that one indicator could be classified in more than one component or scale.

that was inquired at the smallholder scale. Similarly, for the NCP regulation of freshwater quantity, the indicator "access to water" was measured by the number of wells per cover type that each smallholder had (i.e. *benefits* from NCP).

The components of *co-production* and *management* have been assessed by using an even number of indicators at the three scales (Fig. 4). For instance, the indicator 'pastureland surface' that is used to describe the material NCP of fodder was measured across scales. When 'pastureland surface' was measured at the *individual plot* scale, it indicated how people manage their plots [55]. When it was measured at the *smallholder* scale, it monitored the smallholders' decisions on how much of their land is devoted to cattle ranching [50]. Finally, when it was measured at the scale of the *land tenure unit*, it represented how collective decisions are expressed in the communal land [46,54].

We also found that some subcomponents were monitored more frequently than others to assess a particular component (Fig. 5). *Ecological supply* was mainly assessed across scales by indicators referring to the ecological structure (40 % of indicators within the *ecological supply* component), such as plant biomass, forest cover, land use or soil depth. Indicators representing ecological functions (38 % of indicators within the *ecological supply* component), such as evapotranspiration, organic material, or net primary productivity, were only measured at the *individual plot* scale.

The *co-production* component was largely assessed across scales through the exploration of the individual human resources needed to manage their plots (e.g., skills, knowledge), i.e., human capital (57 % of the total indicators within *co-production of NCP*). The component of *management* was mainly assessed with indicators representing intensity (40 % of total indicators within management), such as burning frequency or cattle density, as well as representing time (38 %), such as the number of years managing the plot. To describe the *demand,* most studies used indicators collected at the *smallholder* scale referring to values in general (56 % of total indicators within *demand*). Finally, most indicators used to measure *benefits from NCP* referred to smallholders' livelihood security, such as income strategies (58 % of total indicators within *benefits*), which was largely assessed across scales (Fig. 5).

Moreover, the assessment of the indicators used to characterize the different components in the Chamela-Cuixmala region revealed that while ecological studies used a small set of indicators to measure *ecological supply,* studies measuring *co-production* components led to a proliferation of indicators across scales, particularly for the subcomponent of human capital (Fig. 5).

4. Discussion

In this study, we have operationalized an analytical framework to understand the complexity of SESs through characterizing and describing the NCP across decision-making scales, and tested its representability in a case study of the Global South. In the following, we discuss the frameworḱs innovations and the insights gained from its application in the Chamela-Cuixmala region.

4.1. A novel way to characterize and describe SESs: operationalizing IPBES and EESV frameworks

Our framework showed that key components such as the nature of the *management* regime had not been addressed either by IPBES or EESV, and yet have been strongly emphasized by different social-ecological research communities, including the Long Term Ecological Research Network [31,56] and specific studies, such as Torralba et al. [57] and

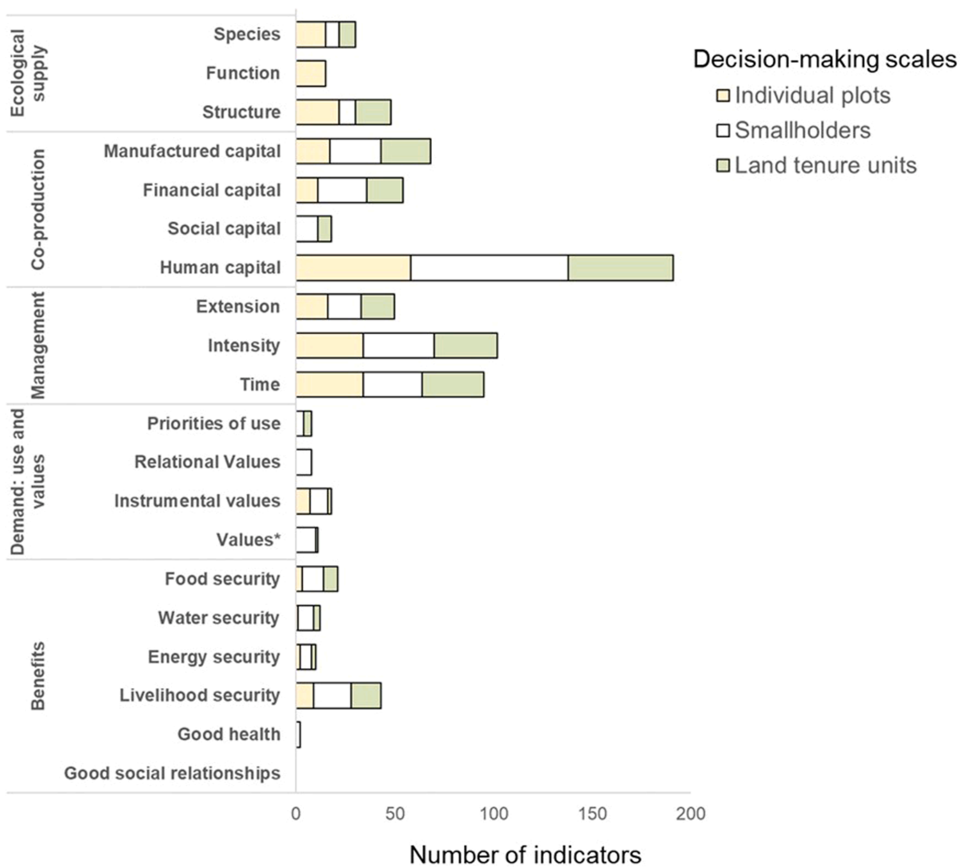

Fig. 5. The number of indicators used to characterize the different components and subcomponents of the SES framework in the Chamela-Cuixmala region across decision-making scales. *We could not distinguish the meaning of some indicators used for NCP *values* and therefore unable to classify them into relational and instrumental values.

Plieninger et al. [58]. Moreover, the analytical framework proposed in this study showed the essential role of the governance of *NCP co-production*, a concept that has been increasingly emphasized by the social-ecological literature [21,59–61]. In addition, we believe that our analytical framework contributes to the heuristic tool of the NFF that is grounded in the plurality of positive relationships between humans and nature [62]. The NFF facilitates the co-creation of innovative scenarios that integrate diverse management interventions aimed at fostering positive future trajectories for nature and NCP [17]. The scenario development process comprises five distinct methodological phases: phase I involves the development of a vision and storyline through a participatory workshop, phase II focusses on actor engagement to address gaps in the visions, phase III is the formulation of the NFF based on analysis of the elaborated visions by the expert group, and in phase IV the NFF is further refined through actor engagement. Finally, Phase V consolidates the scenario narratives that can be used by diverse research communities, including modellers [17]. We believe that our proposed framework offers particular value in Phase I—visioning and storyline development - because the deductive-inductive process used to identify variables and indicators allow the emergence of SESs components that had not been taken into account enough in the scientific literature and are critical to shape SESs, such as the component of *management*.

Our analytical framework advances the IPBES and EESV frameworks in three different ways: 1) the integration of anthropogenic assets and governance as key elements of the *NCP co-production*, 2) the integration of the different values associated with the interaction between people and nature within the *demand* for NCP, and 3) the operationalization of the NCP concept across scales. The integration of anthropogenic assets and governance as key elements of *NCP co-production* to study SESs complexity can provide useful information to determine management strategies that sustain the flow of NCP [22,59]. Our research showed that *NCP co-production* and *management* are central to mediating NCP provisioning. Power relations shape the *management* of NCP and their *co-production* by influencing how actors can access and benefit from NCP [63] or access and use the capitals underpinning *NCP co-production* [64], as well as by determining who can participate in the management of NCP [65,66]. Despite the relevance of power relations mediating SESs complexity, they remain an essential knowledge gap. Recent voices have called for the need to study how power operates shaping the NCP supply, demand, and governance to lever sustainability and social justice, e.g., [64,67,68] and this framework may contribute to analyze who exerts power over whom when managing the capitals behind *NCP co-production,* at what scale and how power is exerted in practice [61,64,69,70] to determine how power can be effectively exercised to foster sustainable and just *management* of NCP.

The consideration of the *Demand* as the component that modulates not only co-production but also people's quality of life (Fig. 3, [21,39, 71] has been identified as one of the most important knowledge gaps to achieve sustainability [67]. Although the operationalization of the suggested framework revolved around the beneficial NCP, the NCP paradigm also considers the detrimental contributions from nature to people, such as disease transmission or predation that damages livestock [15]. In addition, considering the metacoupling of SESs [61], demand of NCP within capitalistic structures driven by mass consumption and economic growth in richer regions can lead to an asymmetric exchange relationship of NCP with poorer regions [72], in turn reinforcing unsustainable resource uses and degradation of, e.g. relational values [73]. We believe that future research can apply this framework to assess both beneficial and detrimental contributions, how they impact people's quality of life, potential conflicts between actors or who are the winners and losers, e.g., [74,75]. That will allow evaluating the effectiveness of management strategies to enhance the sustainable flow of beneficial NCP while reducing impairments from nature and potential conflicts between actors.

4.2. Framework operationalization: insights from a Global South case study

The relative importance of each component depended on the indicators for which data were available at the time that the revision was made (up to 2019). When grounding our generic framework (Fig. 3) to the results for the specific context of the Chamela-Cuixmala region (Fig. 6) we can apply it to one of the key NCP, food and feed, to explore the insights obtained from NCP food and feed. This NCP is one of the most studied in the area and serves as an effective proof of concept for characterizing available indicators and examining how the framework performs in practice. Operationalizing our framework in the long-term social-ecological research site of Chamela-Cuixmala showed (a) the central role of *NCP co-production,* (b) differences in the availability and standardization of the indicators, and (c) varying levels of operationalization depending on the decision-making scale.

First, the operationalization of the framework demonstrates the central role that *NCP co-production* plays in the analysis of SESs across scales, see also [76,77]. In particular, human capital, i.e. the knowledge that supports how SESs are managed, and financial capital, i.e. the resources available to operationalize specific decisions were central to the dynamics in Chamela-Cuixmala blue largest central box in Fig. 6). Institutions and governance, while not explicitly tackled here, emerged both from the papers assessed and in recent explorations as an important driver of NCP in SESs. In fact, [71] have shown that collective decisions lead to reduced management intensity relative to individual decisions, while communal land tenure is associated with less land cover transformations than individual tenure. Both the human and financial capitals supporting *NCP co-production* and the institutions that modulate land tenure and decision making governance modify *management* decisions (dark purple box lower right, Fig. 6) [45,59,60,78]. In turn, those decisions are driven by *ecological supply*, how much food or feed is available and of what nature (green box lower left, Fig. 6). The components of the SESs framework that were less important in Chamela-Cuixmala were those that modulate demand and benefit. This interaction demonstrates how local empirical data can reveal context-specific feedbacks that refine and enrich the structure of the framework beyond what global deductive approaches alone can provide.

Second, we found substantial differences in the general level of availability and standardization of the indicators for the components and subcomponents of the framework. For instance, the indicators of the component *ecological supply* were mostly related to plant biomass, species richness, forest cover, soil properties, plant density, and species abundance (Appendix B). All of these indicators are commonly standardized and available in ecological databases, and their quantification is rather simple at the individual plot scale [2,79]. Similarly, the high standardization level and quantitative nature of *management* indicators were observed across the three decision-making scales and for all the subcomponents (time, intensity, and extension) [50,55,80]. By contrast, although *co-production* indicators were widely used (42 % of the total indicators), the context-specificity of the capitals involved may explain the wide diversity and low standardization of indicators used in the Chamela-Cuixmala region. For example, [81] found that for the supply of fodder in a French Alpine agricultural system there were several anthropogenic capitals involved, including technological equipment, such as irrigation and machinery, financial capital to purchase land or knowledge and skills to decide when to harvest.

We found that, in the Chamela-Cuixmala region, there is a knowledge gap regarding the use of indicators to characterize *demand* (7 %) and *benefits from NCP* (12 %). This gap is particularly relevant in light of recent IPBES developments, such as the Plural Values of Nature Assessment [18] and the NFF [17], which emphasize the need to capture how people value, use, and relate to nature. Indicators of *demand* and *benefits* are precisely the types of variables required to operationalize the Nature for Society and Nature as Culture perspectives of the NFF. These

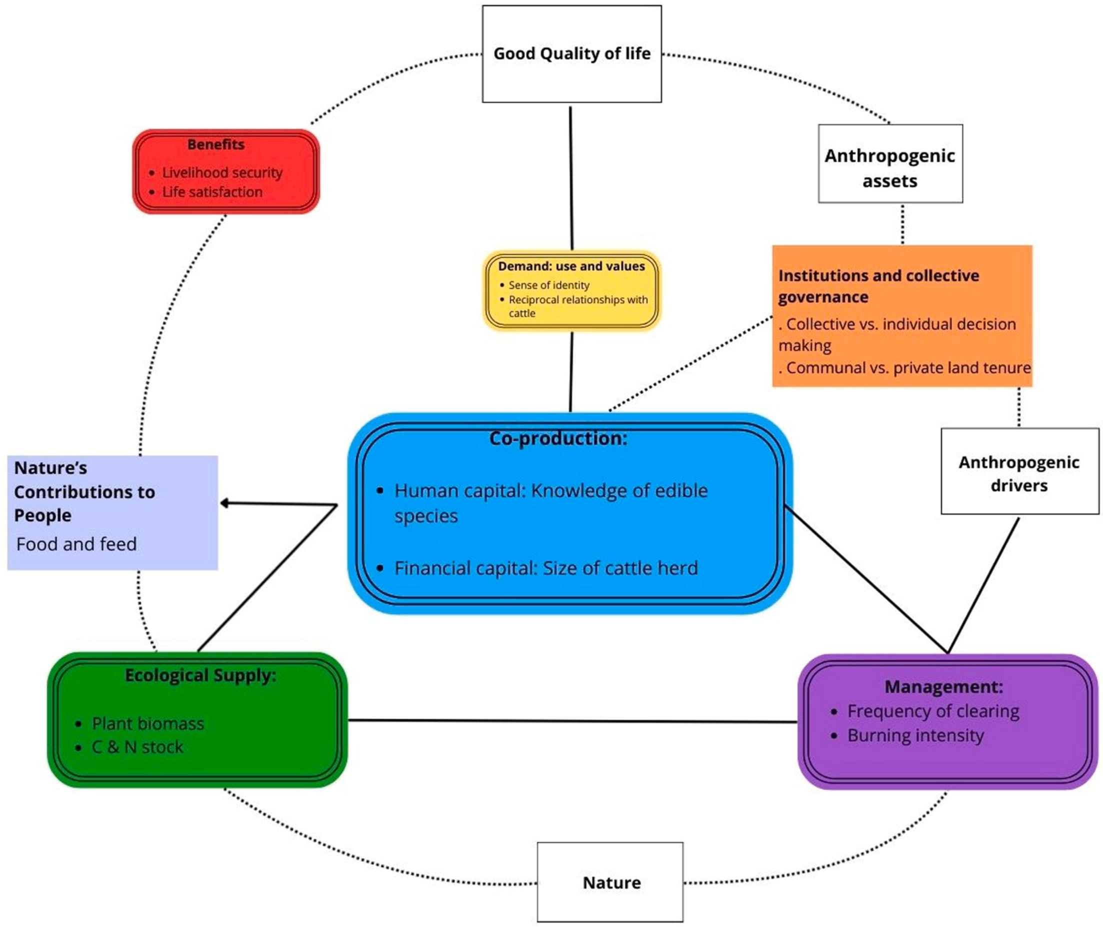

Fig. 6. Exemplary indicators available at Chamela–Cuixmala to characterize the NCP "food and feed," one of the most studied and demanded at the site. The size of the boxes reflects the relative importance of each component for NCP provisioning, based on the indicators available. Although "Institutions and governance" has no associated indicators, recent studies have documented its importance in the co-production of this NCP in the region.

two dimensions capture how people depend on and interact with NCP, and how such interactions shape human well-being and cultural relationships with the environment, interactions that have been documented in the area [39,71]. Our findings are consistent with previous research documenting persistent gaps and limited standardization of indicators for monitoring relational values [67,82–84]. The scarcity of indicators capturing demand, values, and benefits in the Chamela–Cuixmala region suggests that the dominant analytical lens in the area for more than a decade has been the Ecosystem Services framework [31,85]. Emerging frameworks—such as IPBES approaches and the EESV—are only gradually becoming integrated into local research agendas. In this context, our analytical framework represents a crucial instrument for bridging long-standing local approaches with global efforts that seek more plural, comprehensive characterizations of social–ecological systems.

Third, we found that the potential of describing the five components varied according to the decision-making scales. For example, our results showed that *NCP demand* is more suitable to be characterized at the smallholder scale, which aligns with former research on values, e.g., [82,86]. However, the effect of people's values on *management* decisions can result in changes at the land tenure scale [87,71,88]; and on the contrary, supra-local scales (such as communities or farmers' associations) may constitute essential scales to characterize, specially for *management* and *co-production* at which individual decisions are coordinated and sustained and usually have their impacts at local scales. This illustrates the mismatch between the scale suitable for describing indicators and the scale where *management* is reflected. Therefore, by including three local decision-making scales in a framework to characterize and describe SESs, we can show the distinctive, yet interrelated nuances of SESs.

4.3. Applicability and limitations of the framework

Our analytical framework can help deal with the low standardization and proliferation of indicators within certain SESs components by organizing them in several 'tiers' or subcomponents, linking context-specificity with the more general and globally recognisable components as shown in Fig. 6. Our tiered approach identifies a set of components (e.g. *Co-production*), sub-components (e.g. Human capital) and based on key guiding questions (see Table 1) a smaller set of indicators can be identified. For instance, in this case, the knowledge of edible species was deemed critical and thus needs to be prioritized. For the component *co-production*, the most important sub-components are human capital and financial capital. Similarly, financial capital in this area is largely assessed through the size of the cattle herd.

While the proposed framework provides a novel and integrative tool to characterize and describe the complexity of SES, it presents two important limitations. First, despite its grounding in globally recognized frameworks (IPBES and EESVs), its operationalization remains constrained by the availability, standardization, and context-dependence of indicators—particularly for *co-production* and *value*-related components [67,82]; and second, the framework does not explicitly incorporate diverse land tenure regimes, which strongly mediate access to, use of, and benefits from NCP. In the Chamela-Cuixmala case, the *ejido* system -

a semi-collective tenure structure - is central to understanding land management and governance [36,54]. Similar communal systems exist globally, such as *Resguardos indígenas* in Colombia, *Customary lands* in Sub-Saharan Africa, or *Commons* in Europe [89,90], highlighting the need to account for collective institutions and governance arrangements when applying the framework elsewhere.

Moreover, while the framework acknowledges relational values within the *demand* and *benefits* components, these values remain underrepresented in cross-component analyses. Plural valuation, including relational values tied to identity, reciprocity, and place attachment, is especially relevant in contexts governed by communal tenure [20,91]. Relational values not only shape how NCP are perceived and managed [84,88], but also influence power asymmetries, conflict, and collective action [65,68]. As such, future applications of the framework should more explicitly incorporate plural values and the socio-institutional dimensions of land governance to better capture local realities and assess sustainability pathways. This is particularly relevant in the Global South, where collective land systems offer both constraints and opportunities for NCP *management*.

5. Conclusion

The proposed framework strengthens the empirical characterization of SESs by integrating global conceptual developments with context-specific evidence. Drawing on IPBES and EESV while incorporating insights from a Global South case study, the framework captures how *ecological supply, co-production, management, demand,* and *benefits* interact across local decision-making scales. Its application in a local study case reveals which components are most frequently monitored, and where persistent gaps remain. Although it seeks knowledge generalization and indicator standardization, it is intendedly designed to be versatile and flexible to meet the particularities of diverse contexts. Different research questions that can be answered with this framework are related to 1) social-ecological characterization, 2) identification of relevant SESs components and subcomponents in NCP description, and 3) identification of key SESs indicators that allow for the description of NCP interrelations across scales. Therefore, this study provides an analytical way to operationalize global frameworks to characterize and describe SESs across local decision-making scales. Moreover, the inductive identification of interdependencies between nature and people from an empirical Global South case study contributes to informing and further developing global sustainability frameworks.

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Declaration of generative AI use

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CRediT authorship contribution statement

Patricia Santillán-Carvantes: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Berta Martín-López:** Writing – review & editing, Validation, Supervision, Methodology, Funding acquisition, Conceptualization. **Manuel Pacheco-Romero:** Writing – review & editing, Investigation. **Maraja Riechers:** Writing – review & editing, Conceptualization. **Patricia Balvanera:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.sftr.2026.101688.

Data availability

Data are available in the Supplementary material.

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