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Decoupling in governance: the land governance network in a region of the Colombian Andes

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A R T I C L E I N F O

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A B S T R A C T

Land governance requires coherence not only in terms of policies but also between its governance functions to achieve the desired goals. In this study, we focus on the functions that direct influence land use (boundary setting and resource appropriation; project formulation and financing; and monitoring, evaluation, and learning), which are expected to form a feedback loop necessary for adaptive co-management. We evaluated the degree of coherence of these three functions (as an approach to efficient management) via geo-located multilayer social network analysis and using an area of the Rio Grande and Chico basin in the Colombian Andes as the case study. According to the results, there is a conflict between production and conservation goals, necessitating collaboration among actors and institutions from various levels. The social network analysis revealed that the three functions are not articulated; instead, there exist two feedback loops (one per goal) in the *boundary setting and resource appropriation* function, leading to such conflict. The imposition of a *governance system on the community* by a few actors is recognized as the root of this conflict; hence, the need to move toward *a governance with the community* by promoting active participation in the various functions and interactions within them. We recommend future studies to assess the impact of governance networks on land-use actions to identify the reasons for land-use change and propose new strategies.

1. Introduction

Local actors' participation in the design and creation of institutions, their physical proximity, and the impact of their decisions are critical in the context of decentralized land management because of their role in both the supply and demand of environmental services (Agrawal, 2002; Andersson et al., 2014; Armitage et al., 2007; Desta, 2021; Kim et al., 2021; Sayles and Baggio, 2017). As a result, the idea of adaptive co-management emerged, which refers to a long-term, flexible resource management approach based on learning and local knowledge, where responsibility is shared between the community and other actors from different levels (Armitage et al., 2007; Gadgil et al., 2000; Kim et al., 2021; Olsson et al., 2004).

Given the presence of multiple decision-making centers in adaptive co-management, the network of actors who participate in it (Carlsson and Sandström, 2008; Henry and Vollan, 2014) should be analyzed to understand how to create effective arrangements that favor sustainability (Langle-Flores et al., 2017; Sayles and Baggio, 2017). The formation of a governance network depends on the reasons for which actors appear and interact. In this study, we focus on the actors who act and cooperate in land management institutions. Due to the multiplicity of institutions, the concept of *governance functions* is used in works such as those by Paavola (2007), Andersson et al. (2014), and Jiménez et al. (2020) to classify them based on the key factors for successful resource management reported by Ostrom : 90) (1990) and Agrawal (2002). Governance functions, according to such concept, are sets of institutions designed and executed by multiple actors and in various ways for resource management (Andersson et al., 2014; Jiménez et al., 2020; Paavola, 2007); in this case, for land management. In this paper, we are interested in the following three governance functions, which are not exhaustive in terms of management but lead to specific actions on land use:

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- **Boundary setting and resource appropriation (B).** It concerns the development of norms and rules for resource and ecosystem services delimitation, management, use, access, and control (Cox et al., 2014; Dietz et al., 2003; Jiménez et al., 2020; Ostrom, 1990; Paavola, 2007). User boundaries indicate the existence of rules that distinguish between who is a member of a group that can access a resource or ecosystem service and who is not (Cox et al., 2014), and resource boundaries denote the physical boundaries that separate a resource from the broader biophysical environment (Cox et al., 2014). Land tenure (McGinnis, 2011), the formulation of land-use planning instruments, and the standards established by companies on the characteristics of the products are examples of this function.
- **Project formulation and financing (P).** It refers to the construction, development, ratification, and implementation of strategies or projects (Jiménez et al., 2020) aimed at ensuring compliance with rules and providing the necessary infrastructure for land management (Chapin et al., 2009; Dietz et al., 2003). This function considers the acquisition of funds from funding sources to meet project expenditures, as well as the implementation of strategies to disseminate projects. Incentives for agricultural production and marketing, loans, payment schemes for environmental services, job offers, and training in areas of interest are all examples of this function.
- **Monitoring, evaluation, and learning (M).** It is concerned with the gathering, analysis, and use of information on the performance of projects, institutions, policies or, community behaviors (Cox et al., 2014; Dietz et al., 2003; Jiménez et al., 2020). It also involves developing research and generating and exchanging knowledge (Vignola et al., 2013). This function allows for the formulation of new rules or projects and changes in the relationships between actors.

Efficient management in a governance system depends on the articulation or coherence of governance functions (Kardos, 2012), with coherence understood as the synergistic and systematic design and implementation of institutions that contribute to the attainment of a goal (Jones, 2002; Nilsson et al., 2012; Rogge and Reichardt, 2016). Coherence as an approach to efficient management has been studied in terms of policies—see, for instance, the works of Jones (2002), Kern et al. (2019), Rogge and Reichardt (2016), and Nilsson et al. (2012)—, and most studies on actors in the context of land-use and land-cover change have had the same scope (Ariti et al., 2019; Verburg et al., 2015). Despite the relevance of these studies into coherence at the policy level, understanding institutional interactions from a broader spectrum (i.e., from governance functions) is also necessary to comprehend and assess the aggregate effect.

To address this challenge and support territorial planning processes, this study aims to assess the degree of coherence of governance functions in attaining an environmental goal. For such purpose, we characterize a governance network using proxy metrics of the attributes favoring adaptive co-management and geo-located multilayer social network analysis. Such characterization will be performed on a region of the basin of the Grande and Chico rivers in Colombia, which is an important basin for supplying drinking water, food, and electricity to not only the people who live there but also to the rest of the country. In this area, the expansion of the agricultural and livestock frontier has affected strategic ecosystems and water quality (Corantioquia, 2015a, 2015b), suggesting a potential conflict between production and conservation goals and necessitating coordination between actors and institutions to improve land management.

Both participation and cooperation are represented in the characterization of social networks: participation indicates that an actor appears in the network performing an action, and cooperation means that two actors interact in such action. Multilayer network analysis can be used to represent actors' participation and interactions in various actions (Kivelä et al., 2014). This approach, however, has been little explored in governance studies (Berardo et al., 2020); it has been implemented using multiplex networks at the policy level, as in the studies by Schnegg (2018), Langle-Flores et al. (2017), and Locatelli et al. (2020). Additionally, because physical proximity affects interactions (Sayles and Baggio, 2017), the state of the governance attributes is highly dependent on actors' geographic location; hence, geo-located social network analysis should be employed (Andris, 2012; Sarkar et al., 2019). To our knowledge, there are few publications on environmental governance networks that include actors' geographic location, such as those of Rathwell and Peterson (2012) and Huang et al. (2020), and no studies that simultaneously capture the different interactions between nodes in a governance network and their geographic location.

The purpose of this research is to contribute, both theoretically and methodologically, to the understanding of coherence as an approach to efficient land management from broader perspectives (such as governance functions) and with the level of depth required by the analysis of attributes favoring adaptive co-management.

2. Methodology

2.1. Governance seen from the perspective of its functions

The three governance functions[1] described above and depicted in Fig. 1 form a feedback loop that requires the game's rules to be defined (B), a series of projects or initiatives that potentiate changes towards the desired state to be formulated (F), and the effectiveness of the institutions to be monitored and evaluated to identify the necessary adjustments as an adaptation process (M). Efficient management in adaptive co-management depends on the creation of feedback loops that foster learning and better responses in situations of change (Chapin et al., 2009; Olsson et al., 2004).

In Fig. 1, the blue boxes represent the governance attributes, which specify how functions are performed (Jiménez et al., 2020), and the gray boxes represent their contributions to adaptive co-management. When the state of the attributes differs across functions, the actions taken point to different directions, making it difficult to achieve the desired goal. In other words, the degree of coherence of the functions is determined by the state of their attributes.

2.2. Geo-located multilayer social networks

We use geo-located multilayer social network analysis to represent the different interactions between actors and examine the effects of their geographic location. Although social network analysis and spatial network analysis are often addressed separately, analyzing both contexts together can potentially provide more detail about the phenomenon of interest (Luo and MacEachre, 2014; Sarkar et al., 2019). Thus, geo-located multilayer social network analysis serves as a link between the two.

Multilayer social networks allow us to include more than one kind of interaction between nodes: each kind of interaction is represented by a layer, and each layer can follow different dynamics (Kivelä et al., 2014). Based on the notation for multilayer networks proposed by Kivelä et al. (2014), we define network $G = (V, L, V_G, E)$, where $V = \{v_1, v_2, \ldots, v_n\}$ is the set of total nodes that may appear, $L = \{l_1, \ldots l_m\}$ denotes the set of layers that make up the network, $V_G = \{(v_i, l_1), \ldots, (v_j, l_m)\}$ is the subset of nodes that belong to each layer; and the interactions between the nodes are written as $((v_i, l_k), (v_j, l_n)) \in E$. Multilayer networks can be analyzed in aggregate as well as for each individual layer.

[1] In this study, we do not evaluate institutional compliance or the impact of governance functions on land-use actions.

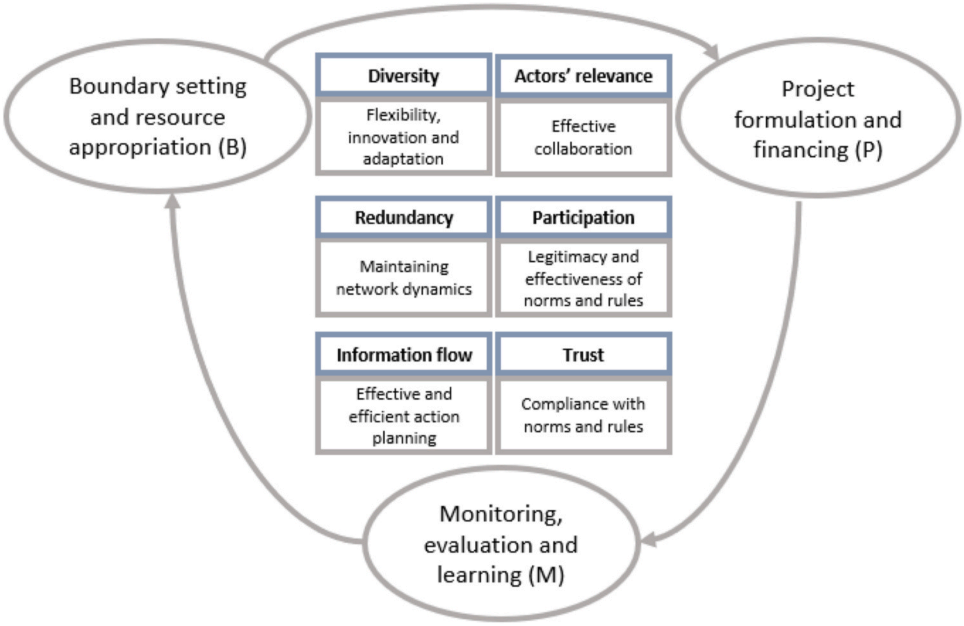

Fig. 1. Feedback loop between the three governance functions considered in this study and their attributes' contributions to adaptive co-management. Governance attributes are displayed in blue boxes, and their contributions are displayed in gray boxes.
Source: Created by the authors based on the studies by Bodin et al. (2006), Carlsson and Sandström (2008), Folke et al. (2005), Janssen et al. (2006), Olsson et al. (2004), Österblom and Sumaila (2011), Ostrom (1990), and Schultz et al. (2015).

When nodes have a geographic location, we refer to these networks as geo-located networks (Andris, 2016). In these networks, each node is assigned a geographic location in the form of (x,y) coordinates (Sarkar et al., 2019). In this study, we consider cooperation links or edges between actors but not their direction or weight. We used Python's NetworkX package to create the network with undirected and unweighted links.

2.3. Case study

As a case study, we consider the upper region of the Rio Grande and Chico basin in northern Antioquia in Colombia (see Fig. 3). This is a strategic basin because there are the Páramo de Santa Inés and the Río Grande II reservoir, which, besides supplying water not only to the people settled in the basin but also to the population in the Valle de Aburrá (second most populated center in the country), meets part of the regional and national energy demand (Corantioquia, 2020a). Moreover,

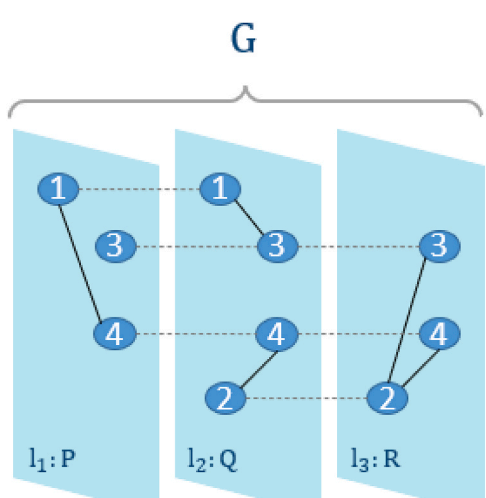

Fig. 2. Example of a multilayer network with undirected and unweighted edges. The solid lines represent the interactions between the nodes, and the dotted lines indicate the presence of the same node in different layers.
Source: Created by the authors using PowerPoint.

dairy farming is practiced in this basin, accounting for a significant portion of the country's dairy production (Berrio-Giraldo et al., 2021). The expansion of the agricultural and livestock frontier in this area, however, has affected strategic ecosystems and water quality (Corantioquia, 2015a, 2015b), necessitating coordination between actors and institutions to improve land and natural resource management.

The basin comprises a total of 127,986 ha (Corantioquia, 2015), of which 24,892 ha are of interest for this study. These hectares are distributed among nine rural settlements in the municipalities of Belmira and Santa Rosa de Osos, and their land cover is illustrated in Fig. 3. Since 2010, there has been a marked increase in land-use and land-cover changes (from non-vegetated covers and crops to pasture), implying that dairy farming has become more appealing to landowners as an economic activity, owing in part to the influence of dairy cooperatives (Díez-Echavarría et al., 2021). According to the life zone classification, the study area consists primarily of Lower Montane Very Moist Forest (bmh–MB) and, to a lesser extent, of Montane Very Moist Forest (bmh–M). Its average temperature is 12 °C, and its annual precipitation ranges from 2000 to 2500 mm (Corantioquia, 2015a, 2015b). The Páramo de Santa Inés, an ecosystem that is critical to the reservoir's drainage system, is in this area. In terms of conservation, the surrounding community is relatively active and participatory (Marsiglia Rivera, 2017), and there are environmental management and protection policies in force, such as the Integrated Management District (IMD), which covers the paramo area (Corantioquia, 2010), and the Local System of Protected Areas (known by its Spanish acronym, SILAP) in one of its municipalities (Corantioquia and Alcadía de Santa Rosa de Osos, 2015). With Colombia's Political Constitution of 1991, the process of decentralization and territorial autonomy started, giving local actors a key role in land management (España, 2020).

We created an inventory of actors and their interactions per governance function (dataset available at (Díez-Echavarría, 2022)) following the three steps in Table 1. First, we identified the actors given the sets presented in the documents. Second, we identified if there are cooperation relationships between actors in each governance function. In this study, cooperation is understood as any regular exchange of any type of information (emails, face-to-face discussions, or material dissemination) or joint work associated with the governance functions. We assume that there is a cooperation link between two actors when the source of information explicitly indicates that they are engaged in an activity related to governance functions. And third, we validated the data

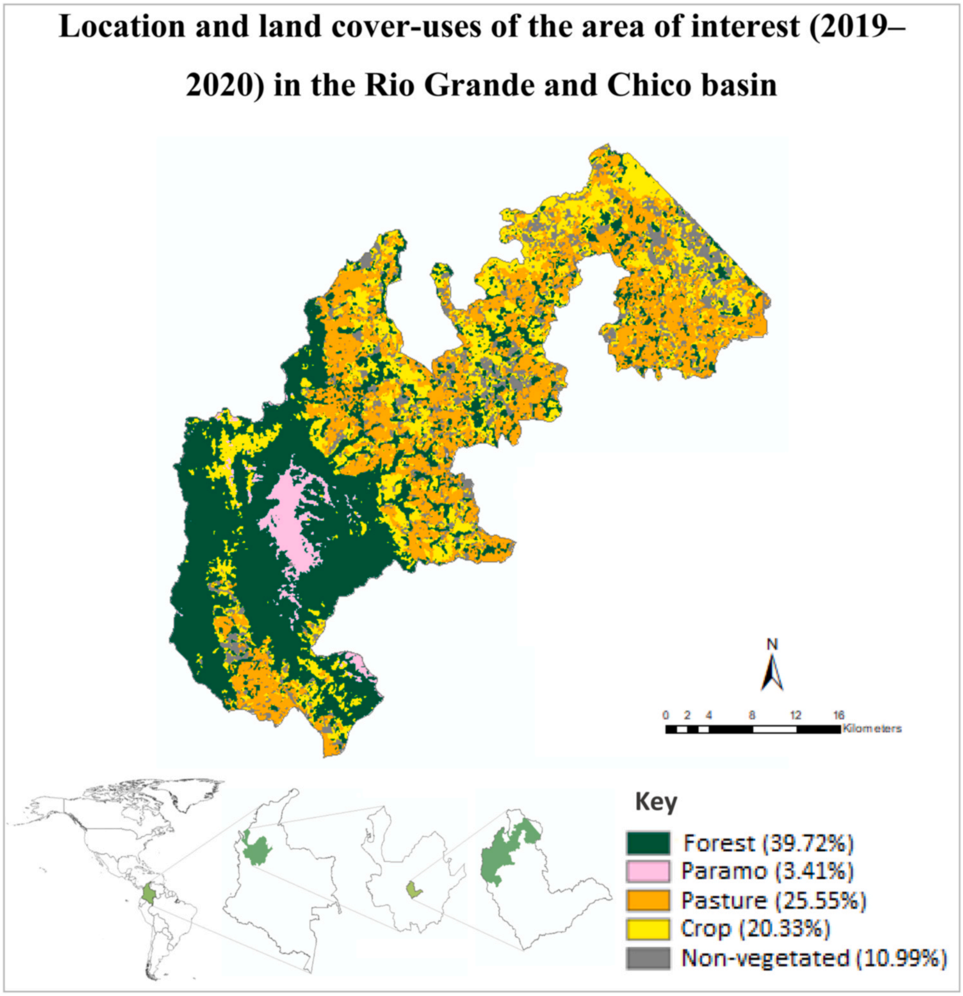

Fig. 3. Location and land cover of the area of interest (2019–2020) in the Rio Grande and Chico basin.
Source: Created by the authors.

through individual interviews, ensuring the responses of at least one actor per class, to have a variety of points of view. To the questions of whether they recognize the actor's presence in the function and their cooperation actions, the interviewees had three response options, two of them when they know the governance dynamics and one when they do not:

a) *the actor participates in the function / the pair of actors cooperate in the activity,*
b) *the actor does not participate in the function / the pair of actors do not cooperate in the activity*, and
c) *I don't know*.

We assume that the actor or link exists if $\frac{\textit{number of positive responses}}{\textit{total known responses}} = \frac{a}{a+b} > 0.65$, where a and b refer to the number of interviewees who selected first or second response option. The threshold is based on the premise that most stakeholders who know the dynamics must recognize the presence of the actor or the relationship in the function for there to be an effect on governance. The validation process is considered sufficient because, although the number of interviews is relatively small, the selected stakeholders are very important in the area.

Table 2 shows a count of the relevant actors in the study area. Each actor possesses the following three non-exclusive characteristics: i) class, which is linked to the actor's goal; ii) type, which indicates whether the actor is of public, private, or mixed nature; and iii) level, which is the extent to which the actor can act. The value that an actor takes in each characteristic is exclusive. For example, an actor cannot be both *economic* and *socio-cultural* in terms of *class*. An actor's geolocation corresponds to a single point in the geographic space, that is, it indicates the actor's main location, which may be inside or outside the basin. Each actor represents a node in the governance network.

It should not be expected that all actors, especially farmers, will come together simultaneously to perform functions; instead, each actor should be able to perform them, even individually and at different times, but then communicate the ideas or decisions to other related actors to build cooperation.

2.4. How are the functions performed? Governance attributes leading to adaptive co-management

Governance attributes are analyzed using a set of metrics (Table 3) related to the context of the nodes and the network. These metrics do not directly measure each attribute but rather provide an approximation based on the network topology. Although traditional network metrics are helpful for characterizing nodes and their interactions, they are not always sufficient to describe the network in its entirety (Andris, 2012). For instance, most metrics focus on the flow of information (Borgatti, 2005) but not on the network's potential to be formed. In the governance context, it is also important to consider the actors who perform functions independently, that is, who are not connected to other actors. For this reason, we use traditional network metrics and propose new ones to further characterize the attributes in both the entire network and

Table 1
Steps to create the network.

Step	Information	Source
1. Actors inventory	Set of economic, political-administrative, and socio-cultural actors	8 reviewed documents:Berrouet (2018);Cardona and Peña (2018);Corantioquia (2020a); Corantioquia and Universidad Nacional de Colombia (2015);Dávila Betancurth (2016);España (2020);The Nature Conservancy and Empresas Públicas de Medellín (2012);Vargas (2020).
	Set of farmers of the civil society	Cadaster Office - Government of Antioquia.
2. Relationships between actors	The role of the actors, work, projects, and other actors with whom they cooperate.	49 web pages of economic, political-administrative and socio-cultural actors.
	The role of the actors, work, projects, and other actors with whom they cooperate.	13 official regulatory documents. Examples: (Corantioquia, 2020a; Corantioquia and Alcadía de Santa Rosa de Osos, 2015; Corantioquia and Universidad Nacional de Colombia, 2015; PNUD and Corantioquia, 2020; República de Colombia, 2017).
	Information of characteristics and field databases of all types of actors.	11 master's and doctoral theses with the same zone of study Examples: (Berrouet, 2018; Cardona and Peña, 2018; España, 2020; Machado, 2018; Marsiglia Rivera, 2017; Vargas, 2020).
3. Validation	We ask about the following elements in each function: • The validity of the definition of governance functions. • Whether she/he recognizes the presence of the actors. • Whether she/he recognizes cooperation actions between actors. • Whether she/he recognizes any actor or relationship other than those mentioned.	Actors interviewed: • *(Socio-cultural actor)* Universidad Nacional de Colombia • *(Socio-cultural actor)* Universidad de Antioquia • *(Civil society actor)* Farmer • *(Economic actor)* dairy cooperative Colanta • *(Political-administrative actor)* Environmental authority Corantioquia • *(Political-administrative actor)* EPM and President of the Basin Council • *(Political-administrative actor)* UMATA Belmira • *(Socio-cultural actor)* ONG Cuenca Verde

Source:Source: Created by the authors.

Table 2
Characteristics of the main actors involved in land management in the study area.

Characteristic	Value	Description	Number of actors	Total actors
Class	Economic	For-profit actors such as companies and cooperatives	5	809
	Political-administrative	Actors that represent the government.	38	
	Socio-cultural	Actors or community action groups and educational institutions.	21	
	Civil society	Population settled in the study area. Farms owners.	744	
Type	Public	Actor with public interests.	35	
	Private	Actor with private interests.	768	
	Mixed	Actor with both public and private interests.	6	
Level	Farm	Action on the property.	763	
	Local	Action in the basin.	27	
	Regional	Action in the department.	8	
	National	Action in the country.	9	
	International	Action in several countries.	2	

Source:Source: Created by the authors.

each layer.

One of the attributes to be analyzed in this study is *diversity*, which refers to the variety of interests, motives, and knowledge. Although the diversity of actors in a governance network might imply higher coordination costs to reach win-win agreements (Ostrom, 1990) and a slower response time (Bodin et al., 2006), it is critical for adaptive co-management to provide flexibility, creativity, and adaptation to change (Carlsson and Sandström, 2008; Folke et al., 2005; Janssen et al., 2006; Olsson et al., 2004; Österblom and Sumaila, 2011; Schultz et al., 2015).

Another attribute we intend to examine here is *actors' relevance*. Identifying the relevant actors in a governance network allows their connections to be managed so as to foster effective cooperation (Biermann and Pattberg, 2008; Bodin et al., 2006; Chapin et al., 2009) within and between governance functions, and such cooperation is one of the foundations of adaptive co-management (Cohen et al., 2012).

Redundancy refers to the network's ability to allow a given function to continue to be performed by other actors if one or more actors are weakened or disappear (Bodin et al., 2006; Janssen et al., 2006). High levels of redundancy help maintain network dynamics, thus favoring resilience in polycentric structures.

Regarding *participation*, it tends to promote institutional legitimacy and inter-actor trust. In other words, the higher the level of participation, the more effective the arrangements might be (Bodin et al., 2006; Ostrom, 1990). Cooperation requires actors to be present when performing the functions and to interact with others. Participation is commonly measured by counting the number of connections in the network (Berardo et al., 2020) or in its subgroups—as in the study by Sayles and Baggio (2017)—, and its flow is of strategic importance for planning responses. These metrics, however, only consider actors who are part of the network and are interconnected, not those who should be part of it or are part of it but in an isolated manner.

The fifth attribute is *information flow*. In a governance network, there are numerous types of information, such as institutions and knowledge (Sayles and Baggio, 2017), and their flow is critical for planning adaptive responses effectively and efficiently (Duit and Galaz, 2008). The flow of this information will depend on the connections between the actors and their geographic location: the closer the actors are geographically (Adán et al., 2020) and the more the connections between them (Sayles and Baggio, 2017), the better the flow of information.

Finally, *trust* is a vital component for adaptive co-management (Olsson et al., 2004). The higher the levels of trust, the lower the likelihood that actors will be enticed to disobey the rules and norms to maximize their individual gain (Baldwin et al., 2018; Ostrom, 2010), which, in turn, could lower monitoring costs (Cole, 2015).

Table 3
Metrics used in this study to analyze the attributes.

Attribute	Metric	Notation / equation	**Relation with the attribute**	**Reference**
Diversity Information flow Trust	Network expanse: topological and Euclidean distance	-	The larger the distance between the actors, the less motivated they will be to follow the behavior of others, which implies that actors could be more diverse, there is less information flow, and it is more difficult to build trust.	(Adán et al., 2020; Borgatti and Foster, 2003; Brucks et al., 2007; Sarkar et al., 2019; Sayles and Baggio, 2017)
Participation	Proportion of present nodes	$P\_n = \frac{n}{N}$ where n is the total number of nodes present, and $N = 809$ is the number of nodes that could appear.	By counting the number of actors who perform the governance functions among the total of actors, regardless of whether or not they are connected, it is possible to have an overview of participation.	-
Diversity	Proportion of nodes: Presence of diverse nodes per characteristic (class, type, and level).	$P\_n_{class} = \frac{\#classes\ present}{Classes}$ where $Classes = 4$ is the number of possible classes. $P\_n_{type} = \frac{\#types\ present}{Types}$ where $Types = 3$ is the number of possible types. $P\_n_{level} = \frac{\#levels\ present}{Levels}$ where $Levels = 5$ is the number of possible levels.	Actors have different characteristics. By counting the number of characteristics that are present among the total, it is possible to have an idea of how diverse the layer or network is.	-
Diversity	Proportion of links: Presence of diverse links or edges per characteristic (class, type, and level).	$P\_e_{class} = \frac{(Clss_{v_i}, Clss_{v_j})}{10}$ $P\_e_{type} = \frac{(Tps_{v_i}, (Tps_{v_j})}{6}$ $P\_e_{level} = \frac{(Lvs_{v_i}, Lvs_{v_j})}{15}$	As the actors have different characteristics, the links between them have different possible combinations. For example, in the case of *type* of actor, there are the following six relationships: private-private, private-mixed, private-public, public-mixed, public-public, and mixed-mixed. By counting the number of combinations that are present among the total, it is possible to have an idea of how diverse the layer or network is.	-
Relevance	Node with the highest topological centrality (degree): number of edges that node v_i has	$a_{ij} = \begin{cases} 1 if v_i and v_j cooperate \\ 0 otherwise \end{cases}$ $D\_v_i = \sum_j a_{ij}$	Actors are considered relevant based on their ability to connect with others, and this ability is mostly determined by the connections they have.	(Battiston et al., 2014; Borgatti, 2005)
Relevance Trust	Node with the highest overlapping degree: number of edges that node v_i has in all three layers	$o_{ij} = \begin{cases} 1 if v_i and v_j cooperate\ in\ the\ three\ layers \\ 0 otherwise \end{cases}$ $OD\_v_i = \sum_j o_{ij}$	Actors are considered relevant based on their ability to connect with others, and this ability is mostly determined by the connections they have. The relationships favors communication and the development of common visions, which are the way to building trust.	(Armitage et al., 2007; Battiston et al., 2014; Borgatti, 2005)
Relevance	Node with the highest betweenness: frequency with which node v_i appears on the shortest path between v_j and v_k	$B\_v_i = \Sigma_{j,k} \frac{SP_{jik}}{SP_{jk}}$ where SP_{jik} is the number of shortest paths from v_j to v_k that traverse node v_i.	Actors are considered relevant based on their ability to connect with others, and the betweenness indicates if a node is an “information bridge” between other two nodes.	(Borgatti, 2005; Brandes, 2010)
Relevance	Node with the highest topological closeness: reciprocal of the average shortest path, $d(v_i, v_j)$, from v_i to all other m nodes it can reach	$C\_v_i = \frac{m-1}{\sum_{j=1}^{m-1} d(v_i, v_j)}$	Actors are considered relevant based on their ability to connect with others, and a node with a high topological closeness value is well positioned to spread information to other nodes.	(Borgatti, 2005; Freeman, 1979)
Relevance Information flow	Node with the highest entropy: distribution of the degree D_v_i of node v_i among the layers	$H\_v_i = -\sum_{l=1}^{L} \frac{D_{vi}{}^{l}}{\sum_{l=1}^{L} D_{vi}{}^{l}} * \ln(\frac{D_{vi}{}^{l}}{\sum_{l=1}^{L} D_{vi}{}^{l}})$ $H\_v_i = 0$ if all the links of v_i are in a single layer, while it takes its maximum value when the links are uniformly distributed over the different layers.	Actors are considered relevant based on their ability to connect with others, not only in one layer but across them, and share information uniformly.	(Battiston et al., 2014; Borgatti, 2005)
Redundancy Participation Trust	Actual density: level of connectivity considering the number of nodes present	$den\_a = \frac{\sum_{i=1}^{n} D\_v_i}{\frac{n*(n-1)}{2}}$ where n is the total number of nodes present	Density measures the level of connectivity in a layer or in the entire network considering the number of nodes present. The more connections, the higher the sense of belonging among actors,	(Bodin et al., 2006; Coleman, 1998)

(*continued on next page*)

Table 3 (*continued*)

Attribute	Metric	Notation / equation	**Relation with the attribute**	**Reference**
			which helps to approach *redundancy*, *participation* and *trust*.	
Participation	Potential density: level of connectivity considering the number of nodes that could be present	$den\_p = \frac{\sum_{i=1}^{n} D\_v_i}{\frac{N*(N-1)}{2}}$ where $N = 809$ is the number of nodes that could appear.	By counting the number of links between actors who cooperate in the governance functions among the total of possible links, it is possible to have an overview of participation.	-
Redundancy Participation	Nodes coincidence: number of nodes that are present in all the governance functions.	$coinc\_n = \frac{n_c}{N}$ where n_c is the number of nodes present in all the layers of the network, and $N = 809$ is the number of nodes that could appear.	The greater the number of actors participating in all the functions, the more freedom there is for any actor to be absent or weakened without affecting the dynamics.	-
Redundancy Participation	Edges coincidence: number of links or edges that are present in all the governance functions.	$coinc\_e = \frac{e_c}{\frac{N*(N-1)}{2}}$ where e_c is the number of links or edges present in all the layers of the network, and $N = 809$ is the number of nodes that could appear.	The greater the number of cooperation links in all functions, the more freedom there is for other links to be absent or weakened without affecting the dynamics. In addition, coordination costs will be lower if each function has the same connected nodes.	-
Redundancy Information flow Trust	Connected components *cc*: independent network portion within the larger network, in which all nodes are connected.	$cc = number\ of\ \ connected\ components$	This measure is an indicator of fragmentation: the more number of connected components, the more fragmented the network is. And the more connections, the higher the sense of belonging among actors, weakening the *redundancy*, the *information flow*, and the *trust*.	(Bodin et al., 2006; Coleman, 1998)
Information flow	Average shortest path length *aspl*: average number of minimum edges that must be traversed to reach all the network's connected nodes.	$aspl = \frac{\Sigma_{i\neq j} d(v_i, v_j)}{e*(e-1)}$ where e is the number of edges or links.	The path length measures how efficiently information travels in the network. Smaller values imply higher efficiency, lowering communication costs.	(Brandes, 2010)
Information flow	Average topological centrality (average degree) *D_aver*: average number of edges in all the nodes present	$D\_aver = \frac{\sum_{i=1}^{n} D\_v_i}{n}$ where n is the total number of nodes present	It is the average number of edges between all nodes present. The higher the average degree, the better the flow of information.	(Bodin et al., 2006)

Source:Source: Created by the authors.

3. Results

3.1. Land governance network

Fig. 4 depicts the social network analysis we conducted based on the proposed methodology. The network consists of three layers, each with a set of actors and their interactions. Even though multiple actors appear in various layers, only the names of those who are in all three layers at the same time are displayed. Antioquia Governor's Office (GOB), mayor's offices (ALC_BEL and ALC_SRO), the environmental authority Corantioquia (COR), and Colombia's Ministry of Environment (MIN_-AMB) are the leading political-administrative actors. The dairy cooperative Colanta (COLANTA) and the dairy company Lácteos Betania (L_BETANIA), are the only economic actors in the network, which indicates their strong influence on land governance. According to Fig. 4, there is a significant imbalance between actors performing each function and the limited number of actors who appear in the three layers (17 actors), which suggests a wide range of interests.

To increase the likelihood of convergence of goals and interests, there should be a minimum spatial distance between actors and governance functions. The smaller the spatial distance between actors, the lower the costs and complexity of their communication, which, in turn, could foster cooperative environments and closer relationships (Choi and Contractor, 2016). We use centroids of the layers as an approximate measure of the location where activities are performed, and to estimate their distance. The centroid of each layer is calculated based on the geographic location of all the actors participating in them. In the case of the network, a weighted centroid is calculated from the total number of nodes V, assigning greater weight to those appearing in different layers; it allows to recognize the role of actors who participate in more governance functions. Then we calculated the Euclidean distance between the centroids, where the smallest values are desired to facilitate fluent communication and cooperation between actors (see Table 4).

The difference in the Euclidean distance values is attributed to the presence of various nodes in each layer: the higher the coincidence in the network, the lower the Euclidean distance between each layer and the entire network. Thus, using the entire network as a reference, the Euclidean distance between its centroid and that of the *boundary setting and resource appropriation* (B) layer was the shortest (3.05 km), while that between its centroid and that of the *monitoring, evaluation, and learning* (M) layer was the longest (52.6 km). Based on this, layer M could imply higher communication and cooperation costs and require greater attention to ensure that interests are aligned with the management goals.

3.2. Analysis of the governance attributes

Fig. 5 and Table 5 show the results of the metrics used to characterize the attributes under study. One of the metrics employed to measure *diversity* was network expanse: the larger the distance between the actors, the less motivated they will be to follow the behavior of others, which implies that there could be greater diversity of actors (Brucks et al., 2007). To analyze distance, we used the social and spatial extents of the entire network and its layers (Fig. 5), which allows to describe not

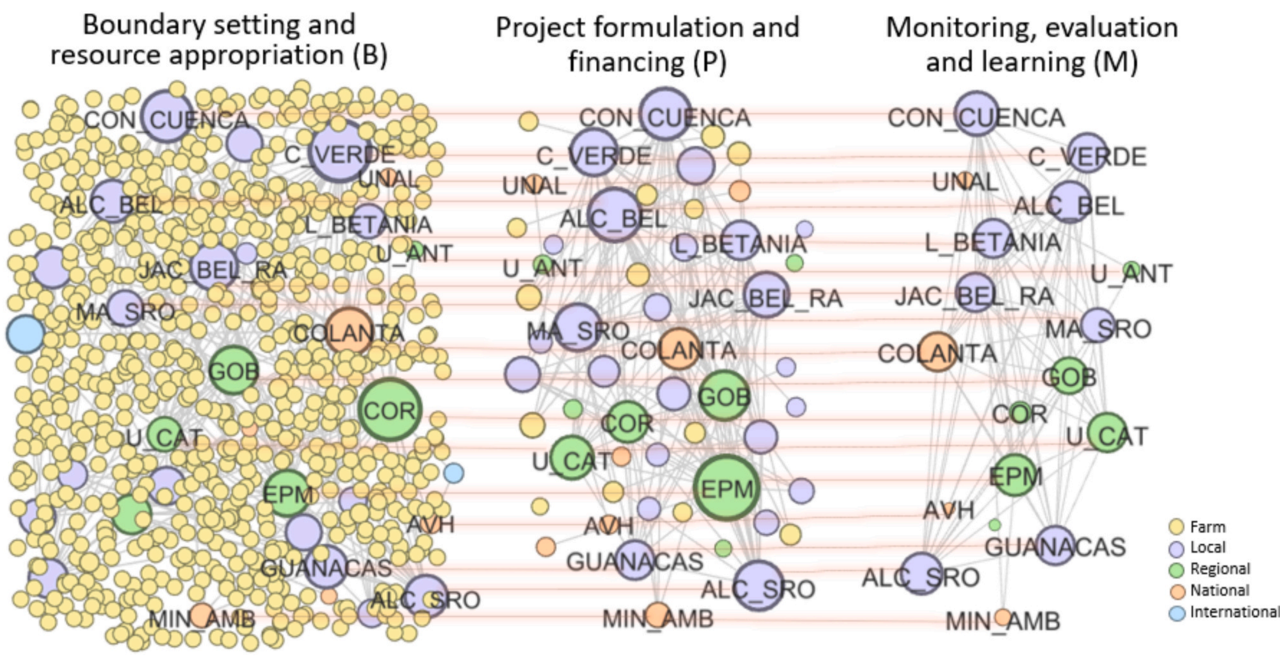

Fig. 4. Representation of the three-layer land governance network in the study area. Inter-layer edges (horizontal brown lines) are associated with the coincidence metric (i.e., they indicate that an actor appears in all three layers at the same time). The size of the nodes depends on their number of connections.
Source: Created by the authors using Gephi and PowerPoint.

Table 4
Euclidean distance (km) between the centroid of the network and the centroid of the layers.

	Multilayer network	B	P	M
Multilayer network	-	-	-	-
B	3.053	-	-	-
P	32.632	35.764	-	-
M	52.636	55.642	20.124	-

Source:Source: Created by the authors.

only spatial but also topological distance patterns. The spatial extent of both the network and its layers was around 300 km, whereas the social extent (or diameter) was 5 nodes for the entire network and ranged from 3 to 5 nodes for each layer. According to these diameter values, every connected node can be reached from any other connected node by traversing relatively few edges.

Similar distances between connected nodes were observed in the entire network and all of its individual layers. In the schemas in Fig. 5, the points concentrated on the left represent interactions between actors who are primarily located in the basin or between the basin and the Valle de Aburrá (which is between 50 and 70 km in Euclidean distance), and those concentrated on the right represent interactions between actors who are primarily located in the Valle de Aburrá and Bogotá (those close to 250 km) or between the basin and Bogotá (those close to 300 km).

As observed, there is a concentration of interactions (points) on both the left and right sides of each scheme, with the left side having a higher density of points. This suggests a spatial autocorrelation principle, which states that elements that are closer (in this case, actors) interact more frequently than those that are farther apart. The premise is confirmed with a global Moran's index for the multilayer network equals to 0.461, and 0.492, 0.457, 0.379, for the layers B, P and M respectively, which means that the links are not formed randomly. In addition, the study area has the highest concentration of actors, and because there are more interactions nearby this area, one may expect greater diversity, which decreases as the Euclidean distance increases.

The other metrics used to measure *diversity* (Table 5) were the proportion of nodes (P_n_{class}, P_n_{type}, P_n_{level}) and the proportion of links or edges (P_e_{class}, P_e_{type}, P_e_{level}) per characteristic. A value of 1 indicates that the network has nodes or edges in all the characteristics of interest, that is, that it is completely diverse in terms of such characteristics. As can be seen in Table 4, the values of the diversity metrics for the multilayer network and the *boundary setting and resource appropriation* (B) layer were high, which favors adaptive co-management (Folke et al., 2005; Janssen et al., 2006; Olsson et al., 2004; Österblom and Sumaila, 2011; Schultz et al., 2015). Although this attribute is important for all functions, it was found to be especially relevant for the *monitoring, evaluation, and learning* (M) layer because it includes activities that promote knowledge, learning, and adaptation (Chapin et al., 2009). This function, however, was the least diverse, as it obtained low values in several metrics.

Relevant actors are expected to support activity coordination and synthesize community knowledge to promote collective action (Bodin, 2017). Table 5 presents the results of the relevance metrics, i.e., the nodes with the highest degree (D_v_i), betweenness (B_v_i), closeness (C_v_i), overlapping degree (OD_v_i), and entropy (H_v_i) values. The higher the value, the better the actor is in a position to spread information to others (Borgatti, 2005; Brandes, 2010). The utility and electric generator company Empresas Públicas de Medellín (EPM), the ONG Cuenca Verde (C_VERDE), the environmental authority Corantioquia (COR), and Santa Rosa Mayor's Office (ALC_SRO), they stood out in the relevance metrics, and Fig. 6 shows the actors with whom they cooperate to perform the functions. EPM, the company that constructed and operates the Riogrande II reservoir, was found to be one of the most relevant actors because it is the node with the most connections ($D\_v_i = 54$ in the entire network) and acts as an intermediary in the *project formulation and financing* (P) and *monitoring, evaluation, and learning* (M) layers. Since this company derives a financial gain from the channeling and treatment of water for human consumption and power generation, it is committed to taking actions to safeguard water resources, which are at the heart of its business model. With its financial gain, EPM is actively involved through relevant actors such as Cuenca Verde (C_VERDE) and its *Fondo de Agua* (Water Fund) program (Cuenca Verde, 2020) and finances several projects developed by Corantioquia

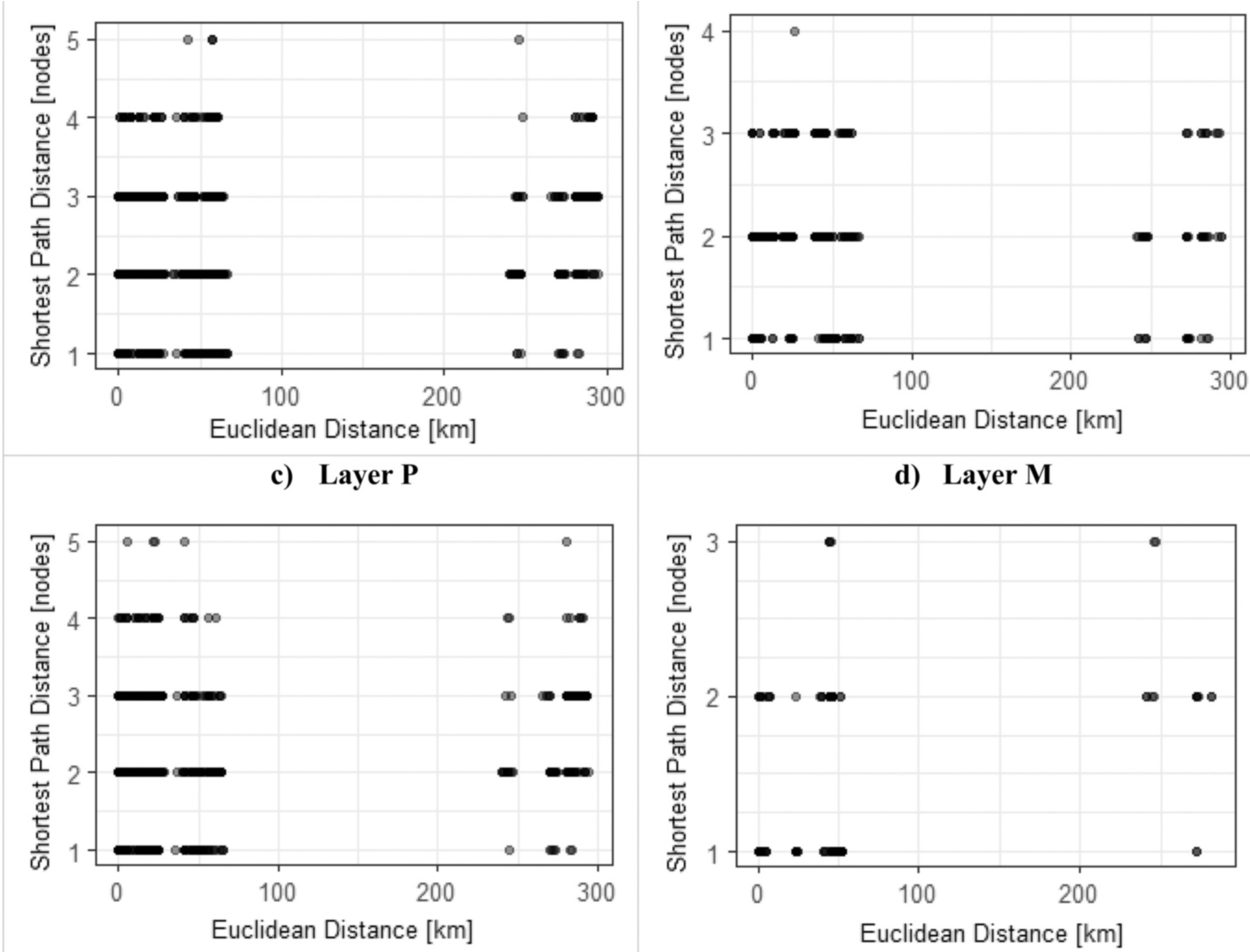

Fig. 5. Expanse schema of the governance network. Each point represents the Euclidean distance (x-axis) and the topological distance or shortest path distance (y-axis) of a pair of connected nodes.
Source: Created by the authors using SpatNet package of R.

(COR) and various mayor's offices in Antioquia (España, 2020) such as ALC_SRO, who has the ability to share information more uniformly across the entire network ($H_{v_i} = 1.008$). Clearly, EPM plays a key role in this land governance network, not only because of its own actions but also because of its participation through other actors.

According to the results obtained for the *relevance* attribute, the government is no longer the centralized entity for land management, as it was only found to be relevant in the *boundary setting and resource appropriation* (B) layer, with Corantioquia (COR)—the regional environmental authority—as the most relevant actor.

Finally, even though universities (UNAL, U_ANT, and U_CAT) carry out monitoring, evaluation, and learning activities to provide technical knowledge (Biermann and Pattberg, 2008), their relevance in the *monitoring, evaluation, and learning* (M) layer was unclear (even though they cooperate with EPM in this function).

To assess *redundancy*, we used four metrics (actual density *den_a*, nodes coincidence *coinc_n*, edges coincidence *coinc_e*, and connected components, *cc*), as well as the configuration of relevant actors. According to the results, the entire network and its three layers showed low redundancy, with *den_a* values below 0.5, low levels of coincidence of both nodes and edges, and a high fragmentation due to the presence of more than two connected components (*cc*). After realizing that the relevant actors in the entire network and in each layer were the same, a high sensitivity to losing them was observed. In other words, the network's current dynamics could be altered if Empresas Públicas de Medellín (EPM), the ONG Cuenca Verde (C_VERDE), Corantioquia (COR), or Santa Rosa Mayor's Office (ALC_SRO) disappeared or were weakened.

Participation was analyzed based on the number of nodes that appeared in the network and their level of connectivity. This attribute was found to be very low in the entire network because of two reasons. First, there was only a 2.1% coincidence (*coinc_n*) of nodes appearing in all functions at the same time (the 17 actors in Fig. 4), and 0.02% of the edges are coincident (*coinc_e*). Second, there was a very low level of connectivity between the nodes, with an actual density (*den_a*) of 0.112% and a potential density (*den_p*) of 0.043% associated with all possible edges.

Two contrasting cases were observed in the results obtained for the *participation* attribute. On the one hand, the function with the highest number of actors was *boundary setting and resource appropriation* (B), with $P\_n = 0.98$, as landowners (744 in total) exercise property rights over their land. However, despite being the layer with the highest number of actors, it was the one in which actors were the least connected, as it obtained a low average degree ($d\_ave = 0.47$) and a low actual density ($den\_a = 0.00061$). On the other hand, although the function with the lowest number of actors was *monitoring, evaluation, and learning* (M), with $P_n = 0.00023$, these actors were found to have a high level of connectivity, with an average degree of 7.79 and an actual density of 0.43. This demonstrates the importance of measuring participation based on both the number of nodes appearing in the network and their level of connectivity with other nodes, that is, not just based on the average degree and actual density but also based on all the

Table 5
Results of the metrics used to analyze the attributes of the governance network.

Attribute	Metric	Multilayer network	Layer		
			B	P	M
Diversity	Proportion of nodes per class (P_n_{class})	1.00	1.00	1.00	0.75
Diversity	Proportion of nodes per type (P_n_{type})	1.00	1.00	1.00	1.00
Diversity	Proportion of nodes per level (P_n_{level})	1.00	1.00	0.80	0.60
Diversity	Proportion of edges per class (P_e_{class})	0.90	0.90	0.90	0.60
Diversity	Proportion of edges per type (P_e_{type})	1.00	1.00	1.00	1.00
Diversity	Proportion of edges per level (P_e_{level})	0.80	0.80	0.60	0.33
Relevance	Node with the highest degree (D_v_i)	54 (EPM)	27 (COR and C_VERDE)	23 (EPM)	13 (EPM and CON_CUENCA)
Relevance Trust	Node with the highest overlapping degree (OD_v_i)	11 (EPM, ALC_BEL, JAC_BEL_RA, COLANTA, L_BETANIA, U_CAT, and CON_CUENCA)	-	-	-
Relevance	Node with the highest betweenness (B_v_i)	337.49 (C_VERDE)	176.90 (COR)	233.56 (EPM)	34.00 (EPM)
Relevance	Node with the highest topological closeness (C_v_i)	0.048 (C_VERDE)	0.036 (COR and C_VERDE)	0.55 (EPM)	0.75 (EPM)
Relevance and information flow	Node with the highest entropy (H_v_i)	1.088 (ALC_SRO)	-	-	-
Participation	Proportion of nodes present ($P\_$)	0.36	0.98	0.068	0.023
Participation Information flow	Average degree (D_ave)	0.97	0.47	5.67	7.79
Participation, Redundancy Trust	Actual density (den_a)	0.00112	0.00061	0.10	0.43
Participation	Potential density (den_p)	0.00043	0.00059	0.00048	0.00023
Participation Redundancy	Nodes coincidence ($coinc\_n$)	0.021	-	-	-
Participation Redundancy	Edges coincidence ($coinc\_e$)	0.0002	-	-	-
Information flow	Average shortest path ($aspl$)	2.26	1.80	2.31	1.52
Information flow Redundancy Trust	Connected components (cc)	749	760	8	3

Source:Source: Created by the authors.

desired nodes, along with their respective desired connections. Differences in terms of participation in the two viewpoints (appearance and connectivity) could suggest a better resource allocation to boost participation in the network. For example, for the boundary *setting and resource appropriation* (B) function, it would be more effective to encourage cooperation between actors through spaces aimed at information exchange or joint work, whereas, for the *monitoring, evaluation, and learning* (M) function, it would be more effective to engage more actors in the various activities related to this function.

As for *information flow*, the spatial and topological distances were similar in the entire network and its layers, as shown in Fig. 5. In general, there is a good flow of information between connected actors, as most interactions are concentrated on the left side of the schemas, where the Euclidean distance is lower, and on the bottom, where the topological distance or shortest path is lower. This finding is supported by the results of the average shortest path length (*aspl*) metric, which revealed that every connected node can be reached from any other connected node by traversing about two nodes (on average). In addition, the *monitoring, evaluation, and learning* (M) layer was found to be the most efficient in terms of information flow, with an average shortest path of 1.52.

Regarding *trust*, the results were similar to those of the *information flow* attribute, as they were found to be better between connected actors. As observed in Fig. 5, most interactions are concentrated in the lower left corner of the schemas, where the Euclidean and topological distances are lower. This is also the case for the 7 actors with higher overlapping degree ($OD\_v_i = 11$), who cooperate with 11 other actors in all functions simultaneously, helping to build a common vision of the management and building trust. It should be noted, however, that trust can be built, and information can only flow through connected nodes, which is where fragmentation becomes a concern. In this case, the number of connected components is the most important metric, which revealed a significant degree of fragmentation, particularly in the *boundary setting and resource appropriation* (B) layer ($cc = 760$) and in the entire network ($cc = 749$)). Considering that the disconnected nodes correspond primarily to landowners, most of whom do not even appear in the *project formulation and financing* (P) and *monitoring, evaluation, and learning* (M) layers, there are two fronts in conflict in the formulation and implementation of land management institutions: (i) civil society actors, who promote agricultural practices through land tenure, and (ii) actors from other classes who favor conservation practices.

4. Discussion

In this paper, we proposed a methodology to characterize the land governance network in a region of the Colombian Andes in order to understand the degree of coherence between governance functions. The findings can be divided into two categories: (i) evidence of imbalance in governance functions and (ii) methodological relevance.

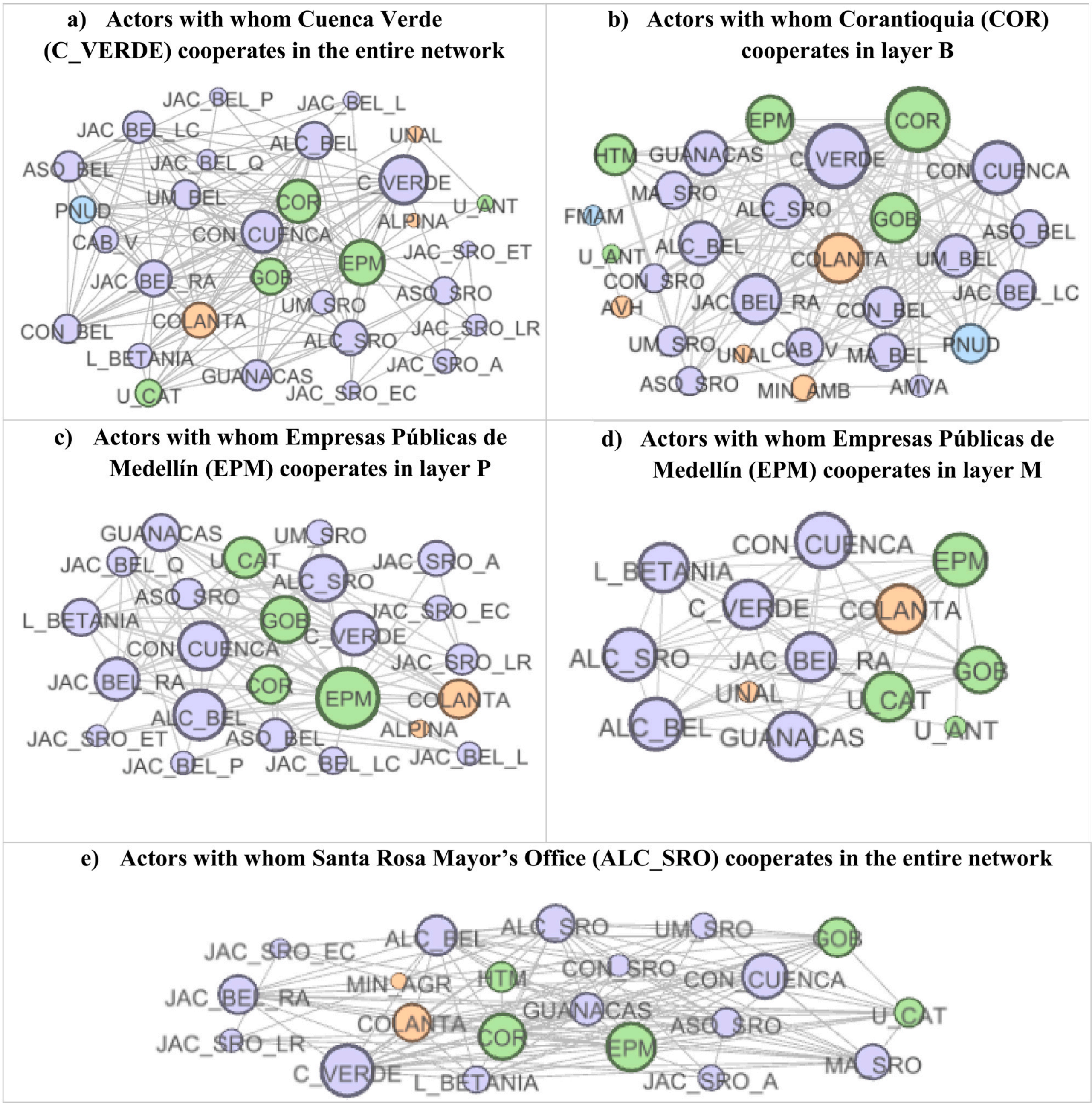

Fig. 6. Connections between the relevant actors in the governance network. Each graph shows the actors with whom the most relevant actor (according to relevance metrics in Table 5) cooperates. The size of the nodes depends on their number of connections.
Source: Created by the authors using Gephi.

4.1. Imbalance in governance functions: two-way governance

The 17 actors that are present in all functions have a greater advantage because they share information in all layers, i.e. they have the view of the complete map. With this advantage there is also a greater responsibility to ensure the objective of land management, leaving for a moment their own interests and the role they have in each function to see the process in a holistic way that forms the feedback loop of adaptive co-management. But, as depicted in Fig. 7, land governance is exercised through two feedback loops, each with its own set of interests. In the loop focused on conservation, we find Cuenca Verde (C_VERDE)—a non-governmental organization—and Corantioquia (COR)—the regional environmental authority—, both connected to EPM (EPM)—a company that is recognized as an intermediary and conservation actor in the area with significant power, financial capacity, and high connectivity to other actors. Betweenness centrality is commonly regarded as a critical factor for network connectivity and information flow (Bodin et al., 2006; Borgatti, 2005; Cohen et al., 2012). It, however, can be problematic when intermediaries use their position to impose their own personal interests (Barnes et al., 2016; Burt, 2004), as appears to be the case with EPM (España, 2020). In the loop focused on farming, dairy organizations (namely Colanta) emerge as the most relevant economic actors in the study area (whose interest is farming). Despite not being key actors in the design and implementation of land-use planning instruments, these cooperatives are highly influential in the area because they bring jobs to the community, which comprises most actors.

In the study by España (2020), there is evidence of a conflict between the two goals mentioned above: (i) conservation, which is led by EPM,

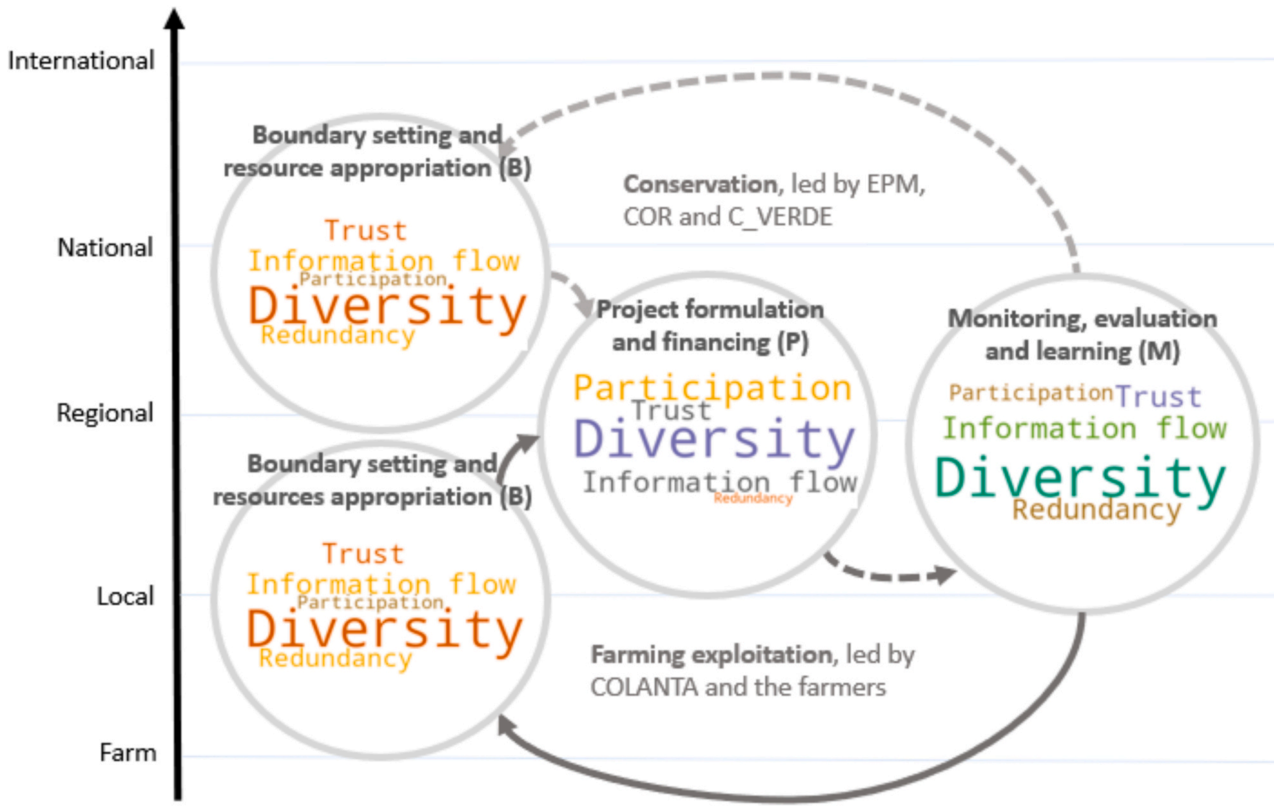

Fig. 7. Feedback loops between governance functions and their two goals: conservation (dotted lines) and farming (dark gray lines). The text size in each circle denotes the weight of the attributes, and the position of the circles indicates the level at which the functions are performed.
Source: Created by the authors using PowerPoint.

and (ii) farming, which is led by Colanta and its associated farmers. Although conservation policies are clearly beneficial to the environment in a variety of ways, landowners' need to obtain a financial gain cannot be ignored because it is extremely difficult to achieve the desired goals if the interests of all stakeholders are not considered. By way of example, the first version of the land-use zoning proposed by Corantioquia as part of its environmental management and protection policy was not adopted by the civil society because, according to such zoning, a large part of the territory should be under strict conservation (Corantioquia, 2020b). We highlight the role that the ONG Cuenca Verde (C_VERDE) and the mayor's offices (ALC_BEL and ALC_SRO) could play to mediate in this conflict because i) they are at the local level, which is fundamental in the adaptive co-management; ii) they are relevant actors in the multilayer network, given that C_VERDE has the highest betweenness (B_v_i) and closeness (C_v_i), ALC_BEL has the highest overlapping degree (OD_v_i), and ALC_SRO has the highest entropy (H_v_i); and in the case of mayor's offices iii) they are not framed in some of the interests: conservation or farming exploitation.

Adaptive co-management particularly focuses on the local level, where difficulties related to management are felt most acutely (Olsson et al., 2004). Even though many local actors participate in the governance network in the study area and cooperate with each other, the community's involvement in land management remains unclear. According to the results of our analysis, landowners were mainly found in the *boundary setting and resource appropriation* (B) layer (because of their land-tenure rights) but in a disconnected way, which usually translates into problematic autonomy when it comes to obeying and enforcing laws, limited trust relationships, and prolonged conflicts (Chapin et al., 2009). Functions performed under this approach, known as the "bottom-up" approach, may be ineffective and unresponsive to local conditions, human livelihoods, and community concerns (Chapin et al., 2009). Hence, efficient co-management requires actions within the *boundary setting and resource allocation* (B) function to be harmonized so that there are no two goals and so that governance is exercised through a single feedback loop. To put it in another way, it is important to move from the current situation, in which few actors impose a *governance system on the community*, to a *governance with the community* by promoting active participation in governance functions and interactions within them.

After analyzing each layer of the network, we found opposite results between the *boundary setting and resource appropriation* (B) and *monitoring, evaluation, and learning* (M) functions in all the attributes under study. For this reason, the strategies focused on the *boundary setting and resource appropriation* (B) function should encourage landowners to cooperate in the formulation or implementation of other institutions, that is, to not only limit to their land-tenure rights in an isolated manner, but also to try to keep an assertive and effective communication with other actors about the ideas that can be turned into norms, for example, with farming organizations and via participation in the community spaces such as Junta de Acción Communal (JAC). Community organizations as Junta de Acción Communal (JAC) are fundamental because they are the direct channel for solving community problems. Meanwhile, the *monitoring, evaluation, and learning* (M) function should seek to engage landowners in the monitoring of institutions and activities aimed at fostering learning and generating knowledge.

Even though the participation of heterogeneous actors in decision-making and collective monitoring has yet to be thoroughly studied from the perspective of environmental governance (Sanches et al., 2021), the *monitoring, evaluation, and learning* (M) function is known to be affected by logistics, technological, and capacity constraints, as well as by a lack of cooperative efforts between relevant actors from the public, private, and third-party sectors (Adu-Baffour et al., 2021). Despite these barriers that must be considered, and as seen in Fig. 4, no farmer formally executes *monitoring, evaluation, and learning* (M) activities, this result can be seen as an opportunity, for example, to devise communication channels to gather farmer perceptions on the performance of all agreements. Since it is the farmers who ultimately decide what use to make of the land, they are the ones who have the most valuable information on the relevance of the standards.

4.2. Methodological aspects

Despite significant progress in the study of efficient land management through policy coherence (Jones, 2002; Kern et al., 2019; Rogge and Reichardt, 2016), analyses in terms of governance functions still need to develop a holistic view. In this paper, we characterized the land governance network in a region of the Colombian Andes to determine the degree of coherence between three functions leading to a specific action on land use. According to the results, the attributes under analysis differed in the three governance functions, and these differences must be recognized to take targeted actions, both for the entire network and for each of its layers. This finding is consistent with what was reported by Tuda et al. (2021), who, despite employing traditional or single-layer networks in their study, discussed the usefulness of multilayer networks when analyzing adaptive co-management. Recognizing such differences across layers should not be confused with separating functions into separate networks, as we are talking about a single process that forms a single feedback loop.

Incorporating the network's geographical component helps to identify nodes and interactions that are likely to be weakened or strengthened, as well as to better comprehend governance attributes. For instance, the *network expanse* metric suggested the presence spatial autocorrelation (and confirmed by Moran's index), a premise under which the network's diversity decreases as attention shifts away from the study area. This is obvious because there are more actors and interactions in the study area, and this density diminishes as the Euclidean distance increases. Importantly, this does not contradict the findings of Brucks et al. (2007), who indicated that the greater the spatial distance between actors, the more diverse they are. Their conclusion actually refers to diversity in terms of the distance between actors, not to diversity in terms of the number of actors and interactions nearby the study area.

Through social network analysis, one realizes that characterizing and understanding a social network depends on the conceptualization of all of its elements (Berardo et al., 2020). Since nodes are the unit of analysis, figuring out what makes them up (individual persons or organizations) is challenging (Newig et al., 2010; Sayles and Baggio, 2017). In this study, we defined the unit of analysis considering the actors who should participate in the formulation or implementation of the institutions associated with each governance function for adaptive co-management to occur, be it individual persons or organizations, as not considering either the two would not reflect reality. A similar conceptualization is found in the study by Juniyanti et al. (2021), although most studies, such as those of Langle-Flores et al. (2017), Locatelli et al. (2020), and Tuda et al. (2021), focus solely on organizations.

In another attempt to get closer to reality, we proposed two metrics: the number of nodes that appear in the network and potential density. In fact, social network analysis focuses on the nodes and their interactions (Borgatti, 2005) but overlooks the importance of identifying actors who should appear as nodes in the network or who appear but are not connected to other nodes. Network density measures the number of potential connections; however, there are no known studies that use metrics that describe possible nodes, such as potential density.

5. Conclusions

Understanding the role of actors in land governance, as well as designing tools to analyze them, is challenging, but it allows us to devise potentially effective strategies for an identified need. In this study, we characterized a governance network using geo-located multilayer social network analysis to determine the degree of coherence between its functions and understand how it can lead to attaining or obstructing the achievement of the desired goals. The results show that, in addition to analyzing policy coherence (which is a common practice), the coherence of the governance functions within which policies might be framed should also be examined. Our findings also demonstrate the advantages of employing methodologies that help to develop a holistic view of governance (as in the case of governance functions) while not overlooking its relationships at more micro levels.

Some land use policy implications arise from the findings of this work, to increase the probability of success. First, policy design should be based on a diagnosis of current conditions, not only physical-biotic but also social, suggesting a convergence between desired land uses on these two fronts. The methodology used in this study is a good way to carry out the social diagnosis. Second, land use policies should clearly contain activities related to each governance function that form a single cycle. And third, it is essential to implement actions to involve the farmers, changing to a governance with the community. They are the ones who choose the land use on their farm, and they are generally the most isolated from the management processes.

Through our proposed methodology, we were able to confirm that the state of each attribute under analysis was different in each layer, that is, the governance functions formed feedback loops aimed at different goals, composed of different actors, and with different levels of action. As a result of this, the probability of achieving any goal decreases; hence, the need to design and implement strategies aimed at reducing the specific imbalances across functions to increase their degree of coherence or articulation. It should be noted that incorporating farmers in the governance analysis generates a high impact on metrics, but such recognition is fundamental in adaptive co-management.

Future studies should consider informal relationships, and they should concentrate on assessing the impact of governance networks on land-use actions and institutional compliance because this would aid in identifying the reasons for land-use change and encourage the formulation of viable strategies aimed at sustainable development.

CRediT authorship contribution statement

Arango-Aramburo Santiago: Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Conceptualization. **Ezzine-de-Blas Driss:** Writing – review & editing, Writing – original draft, Supervision, Resources, Conceptualization. **Díez-Echavarría Luisa:** Writing – review & editing, Writing – original draft, Software, Methodology, Conceptualization. **Villegas-Palacio Clara:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The data is already shared at (see the references list): https://doi.org/10.17632/gfv3kghxcj.1.

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