Environmental Science and Policy 148 (2023) 103550

Contents lists available at ScienceDirect

Environmental Science and Policy

journal homepage: www.elsevier.com/locate/envsci

Probabilistic network analysis of social-ecological relationships emerging from EU LIFE projects for nature and biodiversity: An application of ERGM models in the case study of the Veneto region (Italy)

Elena Andriollo[a,*,1], Laura Secco[a,2], Alberto Caimo[b], Elena Pisani[a,3]

[a] Dipartimento Territorio e Sistemi Agro-Forestali (TESAF), Università degli Studi di Padova, Via dell'Università, 16, 35020 Legnaro, Italy
[b] School of Mathematics and Statistics, Technological University Dublin, D07 ADY7 Dublin, Ireland

ARTICLE INFO

Keywords:
Environmental Collaborative Governance
Social-Ecological Relationships
EU LIFE projects
Ecological connectivity
Protected habitats
Social-ecological network
Exponential Random Graph Modeling

ABSTRACT

Considering social-ecological relationships in managing protected areas is fundamental to ensuring effective biodiversity conservation and restoration governance. Network analysis offers valuable methods to disentangle intangible relations between and within the social and ecological systems. In this way, it could be possible to identify and integrate multiple social and ecological variables that inevitably affect collaborative environmental governance's effectiveness. Nevertheless, this research area is still nascent, with few methodologies and concrete applications reported in the scientific literature. With this study, we aim to propose a robust novel application of a network methodology to enrich the evaluation of the effectiveness of collaborative environmental governance for nature and biodiversity, which has been applied through the analysis of social-ecological relationships that emerged from EU-cofounded LIFE-NAT projects. Specifically, we focus on LIFE-NAT projects implemented in the Veneto Region (Italy) financed in the last programming period (2014–2020). Through formulating four research hypotheses to be tested through Exponential Random Graph Models, we analyze 13 LIFE-NAT projects involving 83 social actors and 29 Natura 2000 (N2000) sites composed of 57 protected habitats. Results show that LIFE-NAT projects in Veneto Region stimulate polycentric governance. Nevertheless, they still need to concretize a multi-actor and multilevel governance. Furthermore, the analysis highlights that selected LIFE-NAT projects implement activities in N2000 sites able to support ecological connectivity and synergies across marine, freshwater, and land habitats through the bridging role of forests, especially in estuarine and coastal areas.

1. Introduction

Recognizing and valorizing interdependencies between society and ecosystems constitute a real challenge to face ongoing environmental problems effectively (Munck af Rosenschöld and Vihma, 2022; Bodin, 2017; Folke et al., 2016; Bodin et al., 2014). Biodiversity degradation, in particular, is one of the most current pressing environmental threats due mainly to human activities, showing that humanity has become a significant force able to foster negative changes at the planetary scale (Roberts et al., 2019; Folke et al., 2016). According to IPBES (2019), humanity is currently experiencing the sixth species extinction, with 1 million species threatened by an increasingly faster extinction rate (Ceballos et al., 2020). To face this problem, one of the essential tools used by environmental governance is the creation of protected areas, which is helpful in the promotion of biodiversity restoration and conservation (Negacz et al., 2022; Cumming et al., 2015). In line with this vision, in the European context, the new EU Biodiversity Strategy targets increasing up to 30% of land and 30% of marine area under protection by 2030 (COM, 2020 380). Nevertheless, even if the size of protected areas has increased in recent years, biodiversity continues to decline (Hermoso et al., 2022; Rada et al., 2018), demonstrating that biodiversity conservation initiatives, at present, have failed to achieve their conservation and restoration objectives (Xu et al., 2021; Gavin et al., 2018). Martín-López and Montes (2015) identify the absence of a

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[*] Correspondence to: Dip. Territorio e Sistemi Agro-Forestali (TESAF) Università di Padova, Viale dell'Università, 15, 35020 Legnaro , PD, Italy.
E-mail address: elena.andriollo@unipd.it (E. Andriollo).

[1] ORCID: 0000-0002-8179-4839

[2] ORCID: 0000-0001-7533-7474

[3] ORCID: 0000-0002-8918-2781

https://doi.org/10.1016/j.envsci.2023.07.010
Received 2 January 2023; Received in revised form 5 June 2023; Accepted 16 July 2023

systemic vision in traditional conservation governance, which focuses on relations between human society and the biophysical system, as one motivation for its failure. In the scientific literature, the fundamental value of social-ecological interactions is highlighted by the Social-Ecological System (SES) concept, which underlines that society is a component of the biosphere and, thus, entirely dependent on nature (Folke et al., 2016; Chaffin et al., 2014). This view has been consolidated in recent years, especially during the Covid-19 pandemic, through the emergence of the "One Health Approach", which highlights that human and animal health is inevitably connected with ecosystems' health (Gruetzmacher et al., 2021).

In the European Union (EU) conservation policy framework, the valorization of social-ecological interdependencies is emphasized by the Natura 2000 (N2000) network.[4] It represents an invaluable example of large-scale conservation initiative based on a uniform system of protected areas across the whole EU territory (Campagnaro et al., 2019), proving to be the largest integrated system of protected areas in the world, covering 18% of EU land area and 8% of EU marine area. It was created in 1992 through Habitat Directive - 92/43/EEC, with the aim to promote biodiversity conservation taking into account both ecological and socio-economic needs (92/43/EEC), and it is composed of protected sites that include areas fundamental for the life of rare and threatened species or protected habitats. Given the centrality of the N2000 network in EU conservation endeavors, it represents the core of the EU conservation approach, which needs to be consolidated, supported, reinforced, and valorized (Hermoso et al., 2022; Campagnaro et al., 2019; Hermoso et al., 2017). The LIFE Programme[5] represents the primary financial source able to sustain N2000 network management (Hermoso et al., 2022; Campagnaro et al., 2019; Hermoso et al., 2017; Sánchez-Fernández et al., 2017). More generally, the LIFE Programme focuses on multiple environmental challenges which need to be faced by EU society, through multiple LIFE projects concerning different priority areas (e.g., nature and biodiversity, resource efficiency, climate change adaptation and mitigation)(EU R. n, 1293/, 2013). Focusing on nature and biodiversity challenges, LIFE is the only EU-funded programme specifically and directly focused on biodiversity conservation and restoration, so it ensures the real implementation of in situ conservation initiatives on N2000 sites (Hermoso et al., 2017). Additionally, the LIFE Programme could be considered an EU tool able to stimulate the emergence of collaborations between multiple and different actors across EU territory, bringing multiple actors through collaboration based on shared objectives to face everyday challenges, thus, constituting a real and tangible example of collaborative environmental governance (CEG) (Munck af Rosenschöld and Vihma, 2022). Additionally, LIFE projects could be seen as concrete examples of polycentric governance arrangements characterized by multiple independent groups of actors that propose actions through a bottom-up perspective using local knowledge and valorizing learning-by-doing processes, fostering adaptation, innovation, trustworthiness, and cooperation between participants (Ostrom, 2010).

To ensure effectiveness in biodiversity activities promoted by CEG initiatives like LIFE-NAT projects in N2000 sites is fundamental recognizing that biodiversity concept does not focus only on the diversity of species and habitats but also on the multiple ways in which social and ecological components relate, assuming different configurations and structures which need to be identified to ensure effectiveness of conservation initiatives (Cumming et al., 2015; Bodin et al., 2014; Bodin et al., 2019). In particular, the social-ecological fit concept underlines the fundamental importance of considering connectivity and interdependencies between social actors and ecological components in order to avoid or solve problems related to environmental management (e.g., asymmetrical use or overuse of natural resources, cascading effects like the spread of invasive alien species, or the depletion of key species in ecosystems), which reveals that very often borders of social activities do not match with ecological borders (Bodin, 2017; Guerrero et al., 2015). CEG could present a valuable solution to face social-ecological fit challenges (Bodin et al., 2016). Nevertheless, collaboration could not be seen as a panacea solution. However, it must be oriented to foster effectiveness in CEG through the identification of structural configurations mostly fitted to environmental challenges they need to face (e.g., more centralized if the problem is urgent, more inclusive when problems cover multiple economic resources) (Andriollo et al., 2021; Bodin, 2017; Bodin et al., 2016; Bodin et al., 2014).

One approach able to integrate social and ecological components affecting CEG is the Social-Ecological Network (SEN) approach based on network analysis (Barnes et al., 2019; Bodin et al., 2019; Sayles et al., 2019; Bodin et al., 2016). Even if network approaches focusing on both social and ecological components of CEG have recently increased, this new research area is still nascent, with a few methodologies and applications reported in the scientific literature (Xiu et al., 2017; Sayles et al., 2019; Bodin et al., 2019). To contribute to such efforts, the specific objective of this study is to *propose and validate a robust novel application of network approach able to enrich the evaluation of effectiveness of the EU collaborative environmental governance through the analysis of social-ecological relationships stimulated by EU co-funded LIFE projects proposed by partnerships*. Even if this study deals only with social efforts to improve nature management and not with any demonstrable on-ground ecological outcome, the proposed approach could be a tool that can offer an additional perspective complementary to other evaluation methodologies already proposed in the literature, focusing specifically on social-ecological interactions through the verification of four hypotheses (Section 2).

After this introduction, we outline our conceptual framework drawing four propositions (i.e., research hypotheses) focused on EU LIFE-NAT projects (Section 2). Then, we present our methodological framework, introducing core concepts, network approaches, and data used for our analysis (Section 3). Next, we verify research hypotheses through ERGM models showing and describing results (Section 4). We discuss the results in the discussions section (Section 5). The article concludes with final remarks (Section 6).

2. Conceptual framework and related research hypotheses

This study aims to reach its main objective by verifying four different research hypotheses (H) that synthesize features able to foster effectiveness in CEG as emerging from experiences reported in the scientific literature. Each hypothesis is translated into specific network structures, which are then verified through Exponential Random Graph Modeling (ERGMs), as proposed by Bodin et al. (2016); Guerrero et al. (2015); Bodin et al. (2014) (see Section 3).

H1 - LIFE-NAT projects promote social collaborations between partners able to concretize multilevel and multi-actor governance. Complexities characterizing environmental challenges require hybrid governance approaches able to integrate different typologies of actors (i.e., the State, market and community), which cannot face environmental problems alone (Lemos and Agrawall, 2006). Additionally, global challenges need to "*Think Globally but Act Locally*", through polycentric arrangements involving actors acting at different jurisdictional levels, from local to global, who act independently but share common objectives (Ostrom, 2010). Therefore, effective collaborations need to include such different groups of actors, connecting them horizontally, across a single jurisdictional level, and vertically across multiple jurisdictional levels (Rigo et al., 2022; Alexander et al., 2017). In this way, partnerships could be more prone to identify shared solutions that overcome jurisdictional boundaries and minimize conflicts and misunderstandings among different stakeholder groups (Andriollo et al., 2021; Alexander et al., 2017; Bodin and Crona, 2009). This capacity is essential in conservation initiatives, which very often are limited by local conflicts

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[4] https://ec.europa.eu/environment/nature/natura2000/index_en.htm

[5] https://cinea.ec.europa.eu/programmes/life_en

generated by local communities who feel exposed to new rules and initiatives that typically originate at higher jurisdictional levels (e.g., at the EU level), potentially limiting their economic activities at the local level (Munck af Rosenschöld and Vihma, 2022; Romano et al., 2021; Staniscia et al., 2019).

H2 - A specific N2000 site represents a well-defined contextual setting for multiple collaborations determined by multiple LIFE-NAT projects. Suppose social actors share objectives and agree on common rules or interventions. In that case, they could use resources more efficiently, compared to the situation where all social actors act individually. They could coordinate efforts concerning the specific characteristics of the N2000 site, avoiding redundant activities, as demonstrated by Bodin et al. (2014) and Guerrero et al. (2015). In LIFE projects, this requirement is already intrinsically embedded in the partnership concept (Munck af Rosenschöld and Vihma, 2022). By adopting a broader vision, the LIFE program to be effective requires collaboration even among different LIFE projects which act in the same area. The wide area approach implemented through diverse projects facilitates a multiplier effect in terms of nature protection and conservation that can help to concentrate the efforts towards a commonly defined strategic and coherent vision, as well as optimize the use of limited-inadequate resources often allocated for biodiversity conservation purposes (Hermoso et al., 2022; Holzer et al., 2019; Popescu et al., 2014).

H3 - LIFE-NAT projects act mainly in N2000 sites that are ecologically connected through ecological corridors. Environmental interventions, like LIFE-NAT projects, aim to replace ecological connectivity to achieve social-ecological fitness of social activities (Bodin, 2017). Accordingly, the network of protected areas realized through N2000 is considered more successful if it can connect multiple protected sites through ecological corridors to allow the movement of species (Hermoso et al., 2022; De la Fuente et al., 2018). Furthermore, ecologically interdependent areas require particular efforts of coordination among interventions and coherent management practices to avoid adverse effects which could emerge from isolated management of protected areas, like the spreading of invasive species (Bodin et al., 2019; Bodin, 2017). This explains why conservation initiatives supported by LIFE-NAT projects need to consider the whole ecosystem in which they act, proposing activities in multiple interconnected areas which represent a different part of the same ecosystem in which they are embedded (Bodin, 2017).

H4 - LIFE-NAT projects stimulate synergic social collaborations among actors and initiatives that implement actions across different habitats. Conservation efforts must synergically act across freshwater, terrestrial and marine realms (Hermoso et al., 2022; Hilty et al., 2020; Hermoso et al., 2017) to increase connections between different but interdependent habitats (Bodin, 2017). As for H3, ecosystems need to be managed as complex systems composed of multiple entities (biotic and abiotic factors and their reciprocal interdependencies), avoiding focusing on a single aspect or component representing only a portion or sub-system of an ecosystem (Bodin, 2017). Thus, collaborations between initiatives spanning different ecological contexts could be a way to create synergies and integrations, translating project results and best practices from one context to another one (Loorbach et al., 2020). Equally, social collaborations between actors of LIFE-NAT projects which focus on different habitats could be a way to ensure functional connections among diverse socio-ecological contexts and better balance economic resource allocation to reduce the heterogeneous distribution of initiatives across EU habitats (Hermoso et al., 2017).

3. Materials and methods

Following previous experiences (e.g., Bodin et al., 2019; Barnes et al., 2019; Bodin et al., 2016; Guerrero et al., 2015), we ground the study on the SES theoretical concept, which is translated through the SEN approach, using stochastic Exponential Random Graph Modeling (ERGM) approaches (Lusher et al., 2013). Detailed information about methodological steps to replicate the proposed approach is available in Appendix A.

3.1. Data selection

This study focuses on LIFE-NAT projects co-founded by the LIFE Programme during its last programming period (2014–2020). In particular, as a case study, we analyze all LIFE-NAT projects acting at least in one N2000 site in Veneto, one of the 19 administrative regions located in the North-East of Italy (Fig. 1). We choose Veneto region because of its richness in LIFE-NAT projects initiatives and its ecological heterogeneity with marine, coastal, river, lowland, hillside, and mountain habitats (ISPRA, 2010).

3.2. Methodological framework

Fig. 2 shows how the SES concept (on the left of the figure) is operatively transposed in this study through the SEN approach. The social system in our analysis is represented by LIFE-NAT projects and LIFE-NAT projects' partnerships which are considered concrete examples of the environmental governance framework proposed by Lemos and Agrawall (2006), highlighting intersections between the State, the market, and the community. In this study, the ecological system refers to the N2000 sites located in the Veneto region and involved in selected LIFE-NAT projects, and protected habitats composing them.

We investigate social-ecological interactions presumably emphasized through the implementation of LIFE project activities through the analysis of three different networks, the Partnership Network (PN), the Social-Ecological Network (SEN), and the Habitat Network (HN), whose components (i.e., nodes and edges) are exposed in Table 1.

In the first network (Partnership Network – PN, in the upper part of Fig. 2) we focus on social-to-social relations through connections created via bottom-up activities of intermediary actors (i.e., brokers), as already analyzed by Pisani et al. (2020) and Rigo et al. (2022).

The second and third networks overcome the purely social-focused analysis and shift the attention towards the social-ecological relationships that emerged through the implementation of LIFE-NAT projects, taking both social and ecological connectivity into account. In particular, the second network -represented in the central part of Fig. 2- aims to visualize a fully articulated Social-Ecological Network (SEN) (Sayles et al., 2019), showing connections between and within LIFE-NAT projects and N2000 sites.

The third network, (Habitat Network - HN, at the bottom of Fig. 2), deepens social-ecological interactions fostered by social collaborations stimulated by LIFE-NAT projects, highlighting how social collaborations connect multiple and different protected habitats that compose N2000 sites.

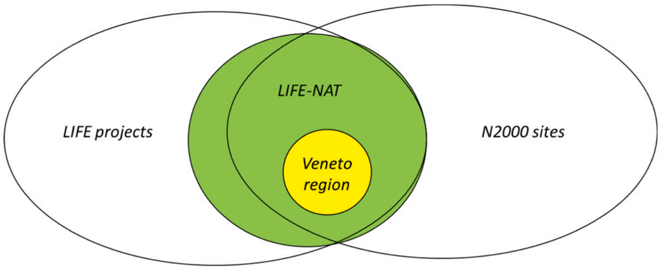

Fig. 1. LIFE-NAT projects selected in this study (in yellow).
Source: own elaboration.

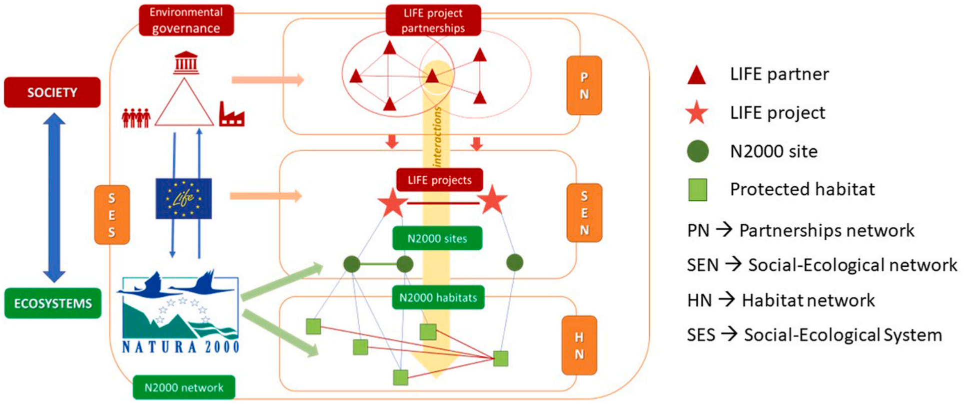

Fig. 2. Methodological framework of the study –
Source: own elaboration.

Table 1
Components of analyzed networks.

Network	Social Nodes	Ecological Nodes	Social-to-Social relations/edges	Social-Ecological relations/edges	Ecological-to-Ecological relations/edges
Partnership Network (PN)	Project partners	-	Collaborations between actors, i.e., partners of the same LIFE-NAT project partnerships	-	-
SEN	LIFE projects	N2000 sites	Sharing of at least one partner in different LIFE-NAT projects	Implementation of LIFE-NAT projects activities in N2000 sites	Ecological connections through ecological corridors
Habitat Network (HN)	-	Protected habitats	-	Collaboration between different LIFE-NAT projects working in the same protected habitat	-

3.3. Data extraction and network creation

Information related to LIFE projects and actors is available on the LIFE Programme website.[6] For this study, we extract information concerning beneficiaries composing LIFE-NAT partnerships and N2000 sites in the target Italian region (Veneto). After then, we add other relevant information about them extracted by consulting another source of data, i.e., the N2000 database provided by the European Environment Agency.[7]

After the data extraction, we classify all nodes distinguishing social and ecological nodes. For every social actor, we specify its jurisdictional level (i.e., local, regional, national and international – Cash et al., 2006), and the typology of actor (i.e., Public Authorities, NGOs, Private Bodies, Universities/Research Centers, and Parks –Avelino and Wittmayer, 2015). After then, we classify habitats following EUNIS (European Union Nature Information System) classification.

Information that is not reported in the previously cited sources, like the typology, the jurisdictional level of actors and the habitat classification, is retrieved through partners' websites (for the identification of type and level) and in the EUNIS website.[8]

Social and ecological nodes are then connected through edges following criteria explicated in Table 1, which highlight social-to-social, social-ecological, and ecological-to-ecological relations. In particular, ecological-to-ecological relations are created following information retrieved through the consultation of the Veneto region PTRC (*Piano Territoriale Regionale di Coordinamento*), which indicates ecological corridors able to connect N2000 sites.[9]

3.4. SEN statistical analysis

Networks are typically analyzed through Social Network Analysis (SNA) which studies relations among multiple nodes defined by edges constituting the analyzed network (Borgatti et al., 2013). In our case, this method can help identify structures and relational patterns between entities represented by nodes, highlighting recommendations helpful in improving the effectiveness of environmental interventions related to the social-ecological fit (e.g., Bodin and Tengö, 2012).

From a statistical perspective, it is essential to highlight that one of the main implications in network analysis is the irrationality of assuming independence between ties composing networks, so it is not possible to use standard statistical methods that assume independence among explanatory variables of the model (Lusher et al., 2013). To solve these problems, Exponential Random Graph Models (ERGM) is one of the most important families of models proposed to statistically develop sound network analyses (Lusher et al., 2013; Wang et al., 2013). They consider the presence or absence of network ties from which structural configurations emerge, to make inferences about behaviors or tendencies of the system under analysis, indicating if there are more or fewer observed structures in the network than expected by chance (Lusher et al., 2013).

3.4.1. Models development

To verify research hypotheses, we develop three separate models referring to the three networks at the bases of this study (i.e., PN, SEN, HN). Model 1 aims to verify H1, Model 2 aims to verify H2 and H3, and Model 3 aims to verify H4 (Krivitsky et al., 2021; Wang et al., 2013; Krivitsky, 2012). The three models are constituted by multiple and different network statistics able to detect tendencies and arrangements of the CEG stimulated by LIFE-NAT projects, which explain whether hypotheses are verified (Tables 2 and 3).

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[6] https://webgate.ec.europa.eu/life/publicWebsite/search

[7] https://www.eea.europa.eu/data-260 and-maps/data/natura-12

[8] https://eunis.eea.europa.eu/habitats.jsp

[9] https://www.regione.veneto.it/web/ptrc/ptrc

Table 2
Network statistics used in models.

Model 1	Model 2	Model 3
Edges	AEdge	Sum
Nodematch_level	BEdge	Nodematch.sum.HABITAT, diff=TRUE
Nodematch_type	XEdge	Transitiveweights.min.max.min
Gwdegree	ATXAX	
	ATXBX	

4. Results

According to the selection criteria applied in this study, as results (R) we identify: (i) 13 LIFE-NAT projects, (ii) 83 social actors composing partnerships, (iii) 29 N2000 sites, and (iv) 57 protected habitats.

4.1. PN network

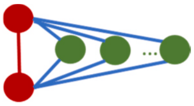
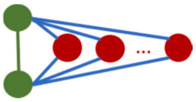
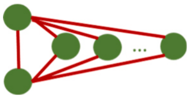
H1: LIFE-NAT projects promote social collaborations between partners able to concretize multilevel and multi-actor governance.

R1: a sparse PN network characterized by homophilic relations.

The PN, shown in Fig. 3, comprises 83 nodes representing all actors involved in LIFE-NAT project partnerships. The network is composed of 24 universities/research centers, 22 public authorities, 14 parks, 13 private bodies, and 9 NGOs. Such actors operate at international, national, regional, and local jurisdictional levels, as shown by 2, 32, 29, and 19 nodes. Universities/research centers and public bodies, including parks, are the most recurrent types of partnership actors, representing 73% of the total nodes constituting PN. Similarly, national or regional levels represent the most frequent jurisdictional levels composing LIFE-NAT partnerships representing 74% of the total nodes in the network. Additionally, through Fig. 3, it is possible to identify three actors making the role of gatekeepers (i.e., central actors able to influence the resource and information flow across the network) connecting multiple partnerships: two universities and one regional authority.

The negative value for both *edges* and *gwdegree* network statistics (Table 4) demonstrate *low density in the network and the absence of variability in the degree of nodes*, meaning the presence of a sparse network without popular nodes composing LIFE-NAT partnerships. On the other hand, the positive value of *nodematch* network statistics for both the level and type of actors show high densities in relationships within the same group of actors, verifying the *tendency to make homophilic*

Table 3
Network statistics used in this study.

Hypothesis	Network statistics	Measure	Statistical Estimation	Network configuration	Estimated behavior
H1	**Edges**	Number of edges in the network	Density of the connections in the network		-
H1	**Nodematch_level**	Number of edges between two nodes characterized by the same level	“Uniform homophily" in the network for "level" attribute		Tendency to create multilevel LIFE partnerships
H1	**Nodematch_type**	Number of edges between two nodes characterized by the same typology of actor	“Uniform homophily" in the network for "types" attribute		Tendency to create multi-actor LIFE partnerships
H1	**Gwdegree**	Number of edges for every node	Degree distribution in the network		Tendency to foster polycentric governance
H2, H3	**AEdge**	Number of edges within social nodes	Density of social relations		-
H2, H3	**BEdge**	Number of edges within ecological nodes	Density of ecological relations		-
H2, H3	**XEdge**	Number of edges between a social and an ecological node	Density of social-ecological relations		-
H2	**ATXAX**	Number of connected social dyads which share multiple ecological nodes	Triadic closure between two social nodes connected to the same ecological nodes		Tendency to make collaborations between two projects working in the same N2000 site
H3	**ATXBX**	Number of connected ecological dyads which share multiple social nodes	Triadic closure between two ecological nodes connected to the same social nodes		Tendency to implement activities in connected N2000 sites
H4	**Sum**	Sum of the values of all the relations composing the network	Density of the network		-
H4	**Nodematch.sum. HABITAT, diff=TRUE**	Sum of values of ties between nodes having the same attribute	“Differential homophily" in the network, distinguishing tendencies of homophilic interactions for every habitat class		Tendency to foster synergies between different protected habitats through LIFE-NAT projects
H4	**Transitiveweights. min.max.min**	Sum of values of ties which share multiple nodes in the network	Tendencies of nodes to create triadic closures in the network, meaning that two nodes tend to be connected because they share multiple other nodes.		Tendency to make collaborations between projects sharing multiple protected habitats

🔴 Social node
🟢 Ecological node
━ Social relation
━ Ecological relation
━ Social-Ecological relation
a, b Nodes attributes

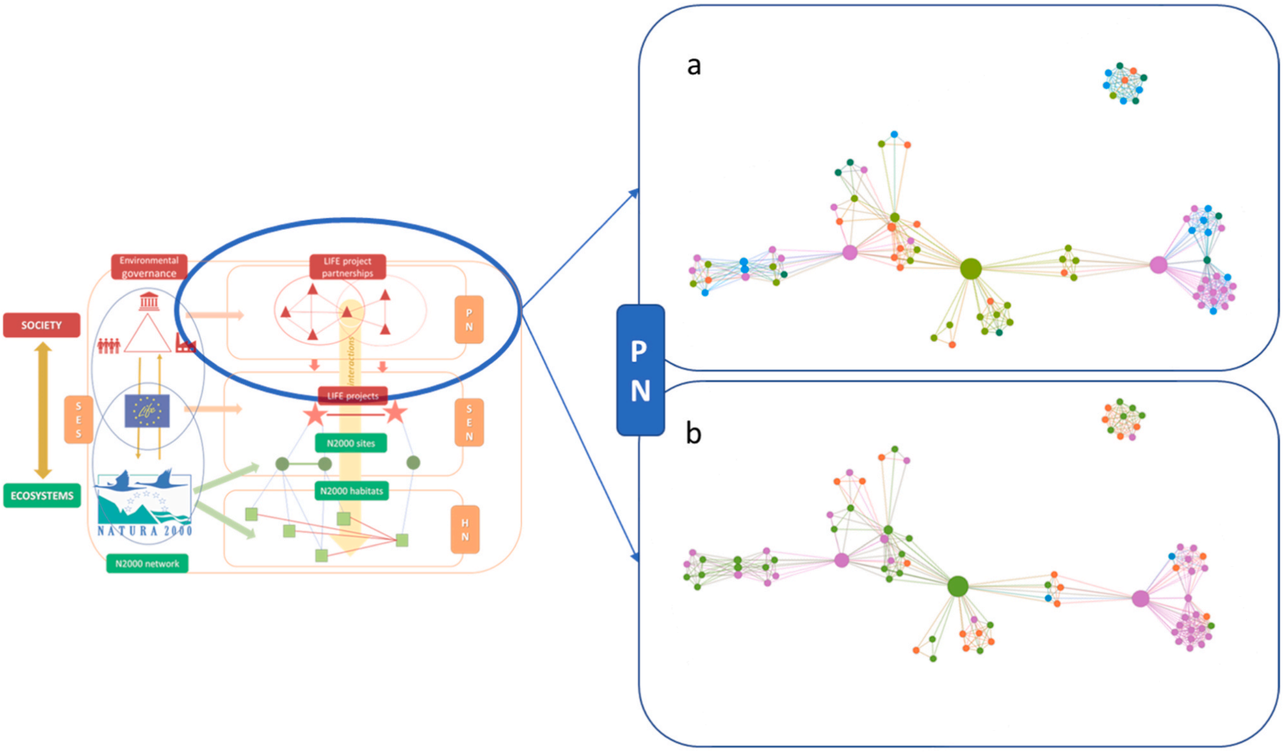


Fig. 3. (a) PN with colors representing the typologies of actors: violet= universities/research centres, green=public authorities, blue= parks, orange= private bodies, dark green=ONG, (b) with colours representing the jurisdictional scale: green=regional, violet=national, orange=local, blue=international.

Table 4
ERGM results for Partnership Network.

	Estimate	Std.	P value
edges	-2.43197	0.08402	P < 0.0001
nodematch.level	0.65215	0.11185	P < 0.0001
nodematch.type	0.81640	0.11758	P < 0.0001
gwdeg.fixed.0.7	-2.54820	0.65737	P < 0.0001

relationships in the network. The model has been tested to verify its stability and goodness of fit.

4.2. SEN network

H2: A specific N2000 site represents a well-defined contextual setting for multiple collaborations determined by multiple LIFE-NAT projects.

H3: LIFE-NAT projects act mainly in N2000 sites that are ecologically connected through ecological corridors.

R2: The nonsignificant value of network statistic does not allow us to verify the hypothesis.

R3: LIFE-NAT projects tend to act in N2000 sites connected through ecological corridors.

The SEN (Fig. 4) comprises 13 LIFE-NAT projects and 29 N2000 sites. It shows that all LIFE-NAT projects are connected through social-to-social ties except for one. Additionally, Fig. 4 shows that most of the N2000 sites where LIFE-NAT projects intervene are connected through ecological-to-ecological connections. Finally, the figure shows that 24% of N2000 sites are involved in more than one LIFE-NAT project and, equally, 61% of LIFE-NAT projects act in more than one N2000 site placed in Veneto Region.

Results of the multilevel ERGM model are reported in Table 5. In addition, the model has been tested to verify its stability and goodness of fit.

The negative values of *AEdge*, *BEdge*, and *XEdge* network statistics indicate that the network is characterized by low values of densities for all types of edges composing the SEN, meaning a sparse network. The results of *ATXAX* network statistics that we used to verify H2 are non-significant. This implies that verifying H2 is impossible. Practically, the model cannot detect if triadic closures are significantly more or fewer than a random graph. Conversely, the significant and positive value of the network statistics *ATXBX*, used to verify H3, demonstrates the presence of triadic closures between couples of ecological nodes which share social nodes, showing that *selected LIFE-NAT projects tend to act in N2000 sites connected through ecological corridors*.

4.3. HN network

H4: LIFE-NAT projects stimulate synergic social collaborations among initiatives that implement actions across different habitats.

R4: Marine and coastal areas foster homophilic relationships. Conversely, forest habitats foster heterophilic relationships.

The HN is constituted of 57 nodes representing different types of protected habitats, specifically, 9 marine habitats, 7 coastal habitats, 8 freshwater habitats, 2 heaths and scrubs habitats, 9 grassland habitats, 3 bogs, mires, fens habitats, 3 rocky habitats and 16 forest habitats. Fig. 5 identifies a set of central habitats in the center of the network that are mainly marine and coastal habitats. Then, a reduced set of other habitats, especially grassland and river habitats, create a peripheral cluster in the network, composed of 9 nodes. Finally, all the other habitats (24 nodes) are placed in the periphery of the network.

To verify H4, the estimated positive values reported in Table 6 related to *nodematch.sum* network statistics show high densities of ties between the first two habitat classes, meaning the *tendency to make homophilic interactions between LIFE-NAT projects focused on sea areas* (habitats classes 1 and 2). Conversely, the significant negative value for habitat class 9, representing forest habitats, indicates the *tendency to make relations between different types of habitats when forests are involved.* Non-significant values for freshwater and grassland habitats (habitat classes 3 and 6) do not allow the demonstration of their tendency to

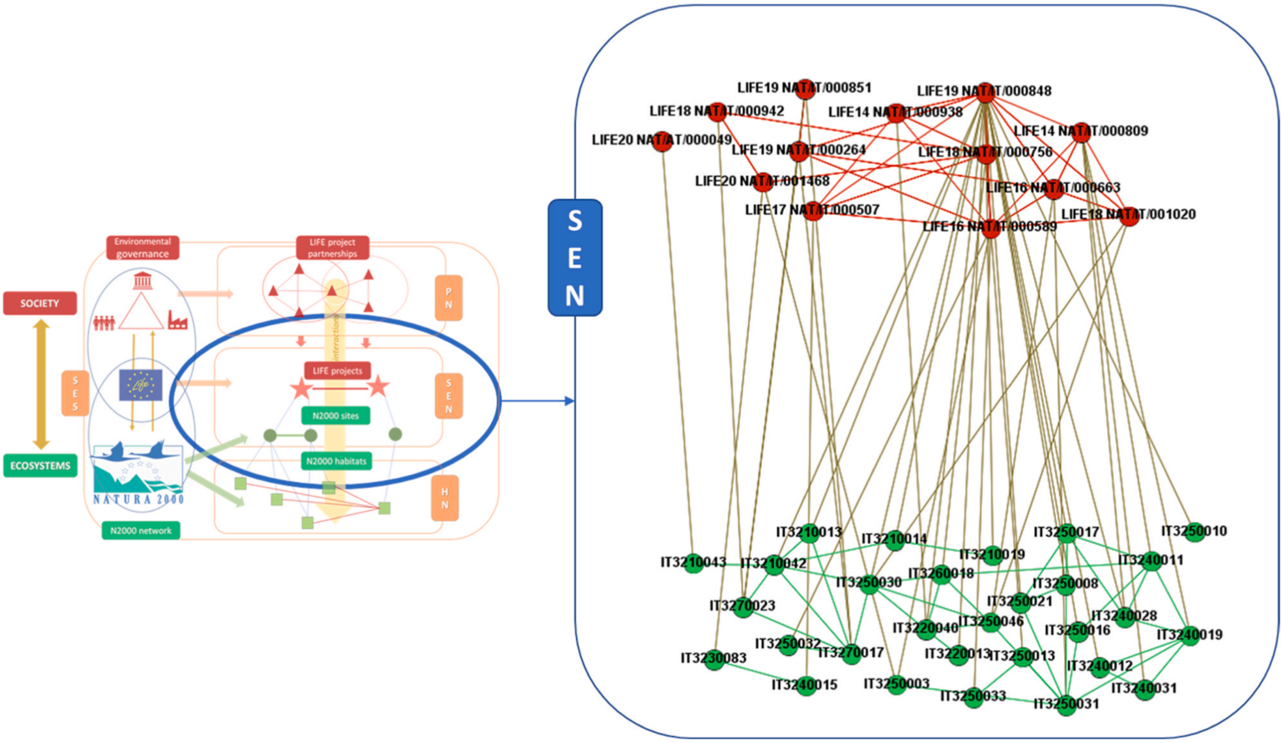


Fig. 4. SEN representation.

Table 5
ERGM results for SEN.

	Estimate	Std.	P value
AEdge	-0.66441	0.256978	P < 0.05
BEdge	-2.60494	0.219204	P < 0.0001
XEdge	-2.75755	0.229168	P < 0.0001
ATXAX	-0.14911	0.435848	n.s.
ATXBX	1.34461	0.165305	P < 0.0001

make heterophilic relations. Therefore, we avoid reporting other habitat classes because they have null values of internal density. Additionally, the high value of *transitive.weight* network statistic reveals the *presence of transitivity in the network*, that is, the presence of triangles composed of three ecological nodes, which concretely highlights that collaborating LIFE projects share multiple habitats. Finally, the model has been tested to verify its stability and goodness of fit.

5. Discussion

In this section where results are discussed (D), we want to highlight that this study is focused on LIFE-NAT projects in Veneto region. Thus, the results that emerged from the analysis do not represent all EU contexts where LIFE-NAT projects are implemented, nor Italy’s national context.

5.1. LIFE-NAT projects and stakeholders

H1: LIFE-NAT projects promote social collaborations between partners able to concretize multilevel and multi-actor governance.

D1: LIFE-NAT projects promote a polycentric governance but fail in fostering a multilevel and multi-actor governance.

The sparse network constituted by LIFE-NAT project partnerships due to the absence of actors connecting with most of the beneficiaries implies that LIFE-NAT projects in Veneto region *create a polycentric governance system* where biodiversity conservation activities are implemented by different and multiple actors who are potentially interdependent in various and complex ways stimulating CEG through bottom-up initiatives (Heikkila et al., 2018; Bodin, 2017; Ostrom, 2010). In this case, polycentricity can be considered a factor that could help stimulate CEG avoiding limitations perceived by people when actions are centralized on a limited number of people ensuring inclusivity and equity across social groups (Gargano, 2021; Bodin, 2017; Newig and Koontz, 2014). LIFE projects represent opportunities to propose environmental projects for a wide range of actors through bottom-up approaches (e.g., Rigo et al., 2022; Pisani et al., 2020). The result demonstrates the capacity of proposing and implementing LIFE projects of multiple and different actors in Veneto region, and thus, their independence in proposing projects. Nevertheless, *the tendency to make homophilic relations across partners implies the failure of LIFE projects in fostering multilevel and multi-actor governance,* as H1 attests the prevalent presence of homophilic relations between public authorities in LIFE-NAT partnerships that already have the jurisdictional responsibility of managing and protecting protected areas (Lai, 2020), and the consequent marginal role of NGOs and private bodies, implies a reduced inclusion of local stakeholders. These tendencies probably reduce the effectiveness of CEG activities like LIFE-NAT projects, limiting the increase of shared environmental responsibility (Andriollo et al., 2021; Campbell-Arvai, 2019; Widman, 2015; Evans et al., 2008). In particular, if LIFE-NAT projects involve multiple and different locals in their partnerships, they could increase the legitimation of activities and, consequently, the prevention or resolution of conflicts, the support of project initiatives from the community, and the prosecution of conservation actions even after the end of the project (Munck af Rosenschöld and Vihma, 2022; Staniscia et al., 2019). Additionally, participation could increase public opinion about biodiversity loss challenges, their repercussions in our everyday life, and the importance of adopting a sustainable lifestyle (Ardoin et al., 2020; Peter et al., 2019). In this way, it could be possible to foster sustainable transformations required to achieve sustainable development goals, which require local interventions to stimulate global changes (Moczek et al., 2021; Loorbach et al., 2020; Folke et al., 2016). Additionally, if locals

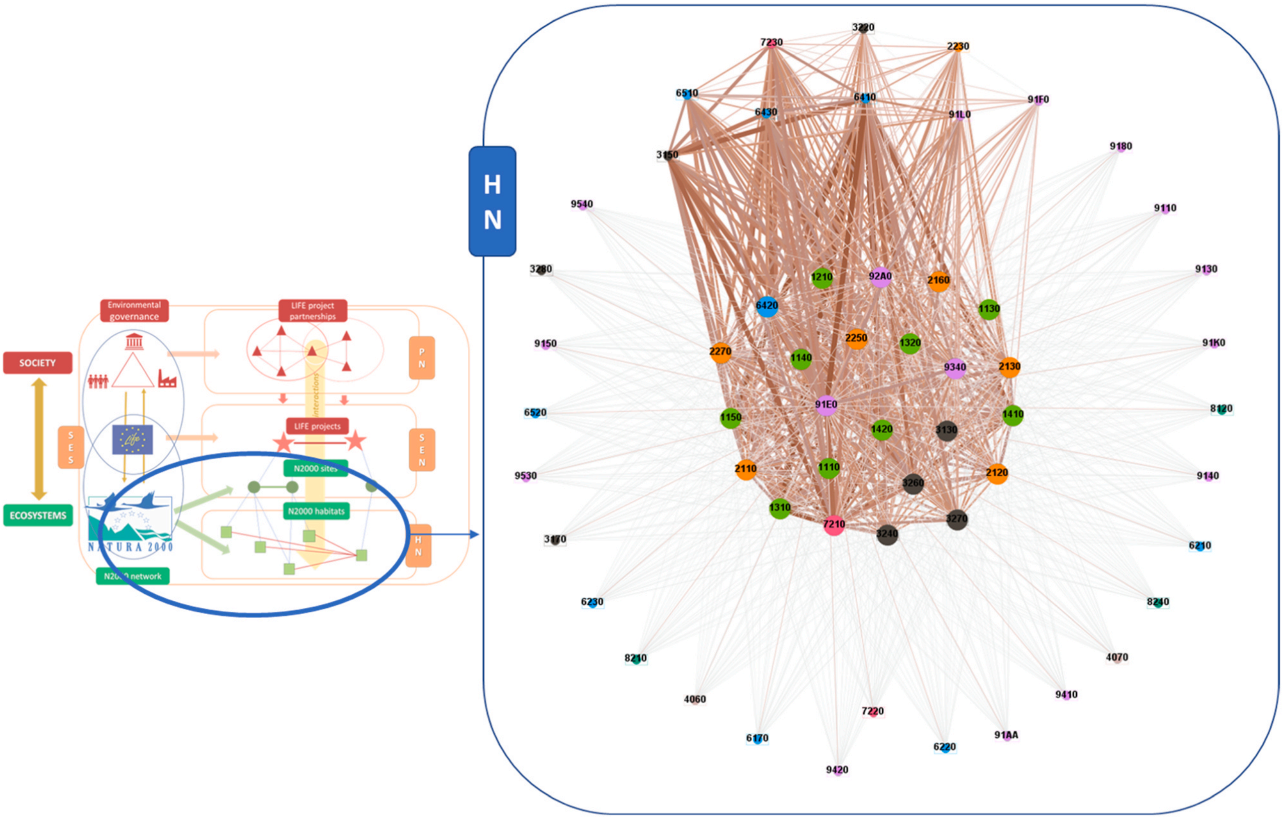


Fig. 5. HN graphical representation. Nodes are coloured according to the EUNIS classification (green= marine habitats, orange= coastal habitat, black= freshwater habitats, brown= heat and scrubs habitats, blue= grassland habitats, pink= bogs, mires, fens habitats, aquamarine= rocky habitats, violet= forest habitats).

Table 6
ERGM results for HN.

	Estimate	Std.	P value
sum	-1.53706	0.20651	P < 0.0001
nodematch.sum.HABITAT1.1	2.78910	0.38325	P < 0.0001
nodematch.sum.HABITAT1.2	0.96424	0.23074	P < 0.0001
nodematch.sum.HABITAT1.3	-0.09563	0.23548	n.s.
nodematch.sum.HABITAT1.6	-0.25100	0.21362	n.s.
nodematch.sum.HABITAT1.9	-1.34725	0.16259	P < 0.0001
transitiveweights.min.max.min	1.13206	0.20683	P < 0.0001

are proactive parts of the LIFE-NAT project, or generally, in the management of N2000 sites, their awareness about EU efforts to face biodiversity degradation is expected to increase, enhancing their truth in public authorities, which at present, in Italy, is low (Tonin and Lucaroni, 2017). Not surprisingly, public awareness of N2000 existence and conservation objectives in Italy, and generally, in all EU territories, is reduced, limiting the successes of the N2000 initiative because awareness is a precondition for a winning conservation policy (Kokkoris et al., 2023).

5.2. LIFE-NAT projects and N2000 sites

H2: A specific N2000 site represents a well-defined contextual setting for multiple collaborations determined by multiple LIFE-NAT projects.

D2: Multiple LIFE-NAT projects act in the same Natura 2000 site. Simultaneous projects allow to tackle the whole range of conservation problems through different tools, allowing to by-pass the possible limit of too much circumscribed specific objectives.

The non-significant value of *ATXAX* network statistic in SEN does not allow for verification of H2. Nevertheless, SEN highlights the presence of many N2000 sites involved in more than one LIFE-NAT project, indicating that *LIFE projects represent opportunities to foster ecological interventions, but they could not exhaustively face the entire conservation challenges of a specific N2000 site* (Munck af Rosenschöld and Vihma, 2022; Hermoso et al., 2017) because projects are limited through specific objectives which focus on particular species or habitats. This is why it is possible to identify more than one LIFE-NAT project simultaneously acting in the same N2000. Therefore, we want to highlight the importance of establishing collaborations between LIFE-NAT projects, which can overcome the intrinsic limitations of projects creating synergies between interventions focused on the same area, integrating conservation objectives in different periods, and, thus, expanding interventions scopes and durations, as required by the needed long-term and holistic conservation approaches (Munck af Rosenschöld and Vihma, 2022; Hermoso et al., 2022; Holzer et al., 2019; Peña et al., 2017).

5.3. LIFE-NAT projects and ecological connectivity

H3: LIFE-NAT projects act mainly in N2000 sites that are ecologically connected through ecological corridors.

D3: LIFE-NAT projects' tendency to act in connected N2000 sites demonstrates advances of the LIFE Programme in managing the N2000 network.

The positive value of *ATXBX* network statistics verifies H3, evidencing that LIFE-NAT projects can support the ecological connectivity of protected areas (Martini et al., 2017; Bodin, 2017). This result makes evidence of *advances fostered by the LIFE Programme in the governance of the N2000 network*, which needs to increase coordinated activities between connected N2000 sites spanning the EU territory (Hermoso et al., 2022). Only in this way, the N2000 initiative could concretize its network nature which gives itself an added value compared with other conservation initiatives like the institution of isolated natural parks (Campagnaro et al., 2019; Martini et al., 2017). In this study, valorizing ecological connectivity is even more important because most of the selected LIFE-NAT projects act in the Padan Plain, which is particularly polluted, disturbed and modified by human activities (Staccione et al., 2022). Additionally, they play an essential role in the social well-being of the local community, offering quiet and natural places inside an urbanized territory, fostering tourism and relaxing experiences (Jones et al., 2020; Jiricka-Pürrer et al., 2019; Schirpke et al., 2018). Previous experiences reported in the literature, like Martini et al. (2017), demonstrate the fundamental role of ecological connectivity across N2000 sites to ensure social and economic outcomes. From a social perspective, promoting coordinated and coherent governance of multiple N2000 sites stimulates traditional and sustainable economic activities and public participation in a wide area (Martini et al., 2017). From an ecological perspective, coordinated management of connected, protected areas is the only way to sustain species that need to move and simultaneously ensure well-managed N2000 sites able to provide resources and shelters to species (Hermoso et al., 2022; Saura et al., 2018; Hermoso et al., 2017).

5.4. *LIFE-NAT projects and habitat synergies*

H4: LIFE-NAT projects stimulate synergic social collaborations among actors and initiatives that implement actions across different habitats.

D4: LIFE-NAT projects establish collaborations able to foster synergies across marine, land and freshwater ecosystems promoted by the transversal role of forests.

The composition of HN reveals that LIFE-NAT projects implemented in Veneto region concern both land and sea habitats. Specifically, marine and coastal habitats located in the Venice Lagoon and Po Delta represent most of the nodes located in the central position of HN. This result implies that the sea environment better stimulates the emergence of collaborations between LIFE-NAT projects implemented in the Veneto region, in contrast to general EU tendencies, which generally focus on land habitats (EEA, 2020; Hermoso et al., 2017). Conversely, the peripheral position of most land habitats refers to the absence of collaboration between multiple LIFE-NAT projects in the continental area of the Region, except for a peripheral cluster, composed especially of grassland and freshwater habitats which refer to protected areas placed across the Padan Plain. Generally, as detected by *transitive.weight*, LIFE-NAT projects are more incentivized to collaborate when they share similar habitats, challenges, and needs. In this way, collaborations between projects represent opportunities to concretize adaptive governance, improving conservation approaches through a learning-by-doing process (Andriollo et al., 2021; Folke et al., 2005). Results identify *coastal and estuaries as core areas where conservation efforts are fostered through collaboration between LIFE-NAT projects*. Specifically, through *nodematch.sum* network statistics, the analysis highlights the bridging role of forests, revealing that selected LIFE-NAT projects stimulate synergies between different habitats when they involve forest habitats. Conversely, LIFE-NAT projects focused on the sea tend to collaborate only if they concern marine or coastal habitats. Such results could be explained by the localizations of most of the LIFE-NAT projects which collaborate, Venice Lagoon and Po Delta. They represent focal areas of land-sea interactions where multiple biological, geochemical, and social processes are strictly intertwined (Fang et al., 2018). This evidence shows the capacity of selected LIFE-NAT projects to *establish collaborations able to foster synergies across marine, land and freshwater ecosystems promoted by the transversal role of forests*. Additionally, such areas also have a cultural and historical value for the regional population to be preserved, facing new challenges related to sustainability achievement (Day et al., 2019). In particular, the city of Venice, which has been nominated as a UNESCO world heritage, needs to face climate change challenges that are more visible than normal (Umgiesser, 2020; Cavaleri et al., 2019). Additionally, the lagoon is generally recognized as an important area for protecting biodiversity frightened by industrialization and petrochemical pollution due to human activities surrounding it, revealing that *collaborative efforts for biodiversity are fostered where human pressures are more perceived* (D'Alpaos and D'Alpaos, 2021; Scarpa et al., 2019; Zonta et al., 2007).

5.5. *Governance implications*

Results obtained through this study reflect how CEG works and how it is possible to improve it by implementing projects like LIFE projects.

LIFE-NAT projects could be considered bottom-up projects open to a wide range of EU actors, requiring high skills and competencies to propose and implement them (Secco et al., 2017). If most territorial actors do not have such skills, LIFE projects will be proposed and managed by a limited number of actors, avoiding establishing polycentric arrangements in the area (Morrison et al., 2019; Bodin, 2017). Thus, they reduce legitimacy, equity, and inclusion (Armitage et al., 2019; Morrison et al., 2019; Ostrom, 2010). Therefore, one of the most important steps required to enhance CEG in a specific territorial area is empowering people by providing education and stimulating their awareness and knowledge of environmental challenges and financial opportunities that could help address them (Armitage et al., 2019; Charles et al., 2020; Gustafsson et al., 2020). Increasing knowledge and skills must be complemented by **inclusiveness and participation of all social groups** in project partnerships (Bixler et al., 2018; Evans et al., 2008). In this way, everyone could perceive himself as an active agent of change, especially local and private actors directly affected by environmental problems and the benefits of project outcomes (Visser-en-Hamakers et al., 2021; Armitage et al., 2019). Practical tools like formal and informal training experiences (e.g., European programming courses or book clubs), public surveys during the identification of LIFE project objectives, citizen science activities, participative evaluation after the end-of-LIFE projects, awareness campaigns proposing experiences like field trips could help stimulate active participation from every social group (Andriollo et al., 2021).

LIFE-NAT projects could effectively sustain and improve N2000 network management when they valorize the concept of **connectivity** (Bodin, 2017; Kininmonth et al., 2015). In line with this perspective, valorizing collaborations between different LIFE project partnerships is fundamental because it stimulates the exchange of best practices and the diffusion of project results, limiting the waste of public resources when effective tools and practices are already tested in previous projects (Bodin, 2017; Guerrero et al., 2015). Additionally, it is fundamental to highlight that the N2000 network is, by definition, a network of protected sites across EU, so LIFE-NAT projects must catalyze social and ecological connections between N2000 sites and the actors managing them (Hermoso et al., 2022; Campagnaro et al., 2019). Thus, LIFE-NAT projects should connect multiple N2000 sites, and stimulate synergies across different habitats. Nevertheless, results show that this point needs to be improved in the future because, at present, collaborations through the implementation of LIFE-NAT projects emerge, especially when projects share similar habitats, highlighting the need to adopt a more strategic vision in the CEG which considers that species live and move across different habitats fundamental for their existence, valorizing **information exchange, coordination and collaboration** between partnerships implementing multiple LIFE-NAT projects (Hermoso et al., 2022; Kühl et al., 2020; Alexander et al., 2017). Furthermore, interactions between LIFE beneficiaries could be enhanced through a new user-friendly tool that shows relations between LIFE beneficiaries and environmental challenges addressed, a shared platform open to all LIFE beneficiaries with materials for activities and results obtained during the projects, and in-person and compulsory events organized by the LIFE Programme authorities.

5.6. *Strengths, limitations, and future application of the methodology proposed by this study*

This study applies a statistically sound methodology (Lusher et al., 2013) to evaluate the effectiveness of EU LIFE-NAT projects. In this sense, it proposes a novel approach that gives robustness to the network analysis (Sayles et al., 2019; Bodin et al., 2019; Bodin et al., 2016). To test the application of such a robust statistical approach to network analysis, we used a regional case study. Nevertheless, the proposed methodology could be used to verify the effectiveness of environmental activities in national and EU contexts, thus getting a complete overview and detailed picture of tendencies in the CEG sustained by the EU LIFE Programme. The same type of analysis could be replicated in all EU contexts because the data used by this study are open-source and available for all EU countries through EU open databases. The only data retrieved from a regional source concern ecological corridors, but, at present, such information is quite explored by the scientific literature, which offers methodologies able to detect ecological corridors if they are not shown by territorial plans, like Popescu et al. (2022). Nevertheless, the methodology has some limitations. For example, it cannot be used to systematically analyze other typologies of LIFE projects because the LIFE Programme database does not give information about their localization. The lack of clear and standardized data about the typologies of actors and their jurisdictional level in the LIFE Programme database implies a classification made by researchers which could be considered arbitrary. In addition, the LIFE Programme does not give information about other stakeholders outside the LIFE project partnership, e.g., co-financier (Rigo et al., 2022). So, the analysis may not detect some important actors involved in LIFE projects. Additionally, focusing on the methodological approach used in this study, we faced multiple data analysis problems because of the reduced availability of analytical tools suited to analyze multilevel networks (see also Guerrero et al., 2015).

Thus, we identify many further progresses that are required to consolidate and expand the SEN research area and produce scientific results that can be useful for policymakers. Firstly, from a statistical point of view, there is a need to improve multidisciplinary collaborations between statistic model developers and applied researchers to develop new tools to model networks representing SES. Secondly, focusing on the specific case of LIFE Programme evaluation, further studies could explore social-ecological relationships supported by LIFE-NAT projects focusing on other Italian regions or various national contexts to compare different EU territories characterized by differences in legal frameworks, cultures, ecosystems, and perceptions. More generally, further studies could apply this framework in the whole EU context giving a general picture of tendencies in the LIFE governance in Europe. This could be useful to indicate how to improve future EU environmental policies and allocations of resources to foster participation and collaborations. Additionally, this methodology could be applied to other periods to analyze the evolution of the conservation efforts supported by the LIFE Programme during the 30 years of its life to detect errors and successes of the EU conservation policy over years using a learning-by-doing perspective. Thirdly, the proposed methodology could be replicated outside the LIFE Programme and N2000 network background, and more generally, outside Europe, in less data-rich contexts, revealing new challenges to get data but also providing opportunities to give new perspectives using this approach with primary data which allow understanding real situations of evaluated contexts (Andriollo et al., 2021).

6. Conclusions

The innovative approach proposed by this study to evaluate the effectiveness of CEG from a network perspective allows identifying advances and limitations of CEG for biodiversity conservation and restoration supported by LIFE-NAT projects implemented in the Veneto region in the 2014–2020 period.

From the analysis of network structures, it is possible to obtain recommendations that could be helpful for policymakers and practitioners to enhance the composition of project partnerships and to identify suitable objectives and intervention areas. PN highlights the need for increased heterogeneity in LIFE project partnerships through the active involvement of market and not-for-profit organizations, acting especially at a local jurisdictional level. The importance of participative processes for biodiversity needs to be clarified, valorized and fostered, especially at subnational levels (i.e., regionally and locally) through the empowerment of local communities.

Additionally, the analysis highlights the need to valorize the concept of connectivity, through LIFE-NAT projects stimulating synergies across different N2000 sites and protected habitats. In this way, they could favor coordination and coherence in the CEG of N2000 network, concretizing a transversal, holistic and coherent CEG of protected areas.

Funding

E.A. is supported by a PhD grant funded by the Department of Land, Environment, Agriculture and Forestry of the University of Padova.

CRediT authorship contribution statement

Elena Andriollo: Conceptualization, Methodology, Data curation, Writing – original draft, Writing – review & editing. **Laura Secco**: Writing – review & editing, Supervision. **Alberto Caimo**: Conceptualization, Methodology, Writing – review & editing, Supervision. **Elena Pisani**: Conceptualization, Writing – review & editing, Supervision. All authors have read and agreed to the published version of the manuscript.

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

Data will be made available on request.

Appendix A

Methodological steps to perform the approach proposed by this study

Conceptualization/Design of networks

This approach aims to analyze social-ecological relationships by investigating three different networks: the Partnership Network (PN), the Social-Ecological Network (SEN), and the Habitat Network (HN).

In the first network (PN), we focus on social-to-social relations through connections created via bottom-up activities of intermediary actors (i.e., brokers), as already analyzed by Pisani et al. (2020) and Rigo et al. (2022). In this study, relationships between LIFE-NAT project partners refer specifically to the mutual collaborative relations among actors sharing environmental responsibility for biodiversity conservation through the proposal and implementation of a LIFE-NAT project in an N2000 site. We assume that such relationships are based on reciprocal communication about interventions implemented by every partner and the exchange of knowledge to identify best available practices (BAT) and foster adaptive learning within the network (Munck af Rosenschöld and Vihma, 2022; Andriollo et al., 2021; Gavin et al., 2018).

The second network (SEN) (Sayles et al., 2019) shows connections between and within LIFE-NAT projects and N2000 sites. In particular, social-to-social connections represents collaborations between LIFE-NAT projects when at least one partner is shared between two projects, social-ecological connections indicate N2000 sites where selected LIFE-NAT project implement their activities, and ecological-to-ecological connections connect N2000 sites that are linked through ecological corridors.

The third network (HN) deepens social-ecological interactions fostered by social collaborations stimulated by LIFE-NAT projects. The network aims to highlight how social collaborations connect multiple and different protected habitats that compose N2000 sites. In other words, protected habitats are connected if at least one collaboration between two LIFE-NAT projects exists. Here the network is weighted, with relations having different values due to the numerosity of collaborations between LIFE-NAT projects insisting on the same protected habitat (Krivitsky, 2012).

Data extraction and network creation

Data are extracted through the LIFE Programme database (https://webgate.ec.europa.eu/life/publicWebsite/search) to perform the analysis. The LIFE database allows to select LIFE projects through queries and filters. After their identification, it is possible to visualize an informative spreadsheet with (i) project description, (ii) administrative data, (iii) contact details of the coordinating beneficiary, (iv) environmental issues addressed, (v) beneficiaries composing the LIFE project partnership, (vi) other information such as the link to the project website.

To verify research hypotheses, we identify suitable LIFE projects, applying as filters (i) the years when they are co-founded, (ii) the typology of the LIFE project (i.e., LIFE-NAT), and (iii) their localization. For this last point, it is required to manually select LIFE projects considering the N2000 site codes where they are implemented, so the final selection of LIFE-NAT projects is possible after data extraction about their implementation in N2000 sites.

After selecting LIFE projects, we collect information related to (i) LIFE project beneficiaries and (ii) N2000 sites where they are implemented. In this way, we can understand who/what are social and ecological nodes.

Data about social nodes representing LIFE projects and LIFE project beneficiaries are then enriched though their categorization. After the data extraction, we classify all nodes distinguishing social and ecological nodes. Additionally, for every social actor, we specify its jurisdictional level indicating international, national, regional, and local levels (Cash et al., 2006) and the typology of actors following the classification proposed by Lemos and Agrawall (2006) distinguishing public authorities (the State), NGOs (the community), and private bodies (the market), adding two more categories: University/Research centers (the third sector, see Avelino and Wittmayer, 2015) and Parks because of their important role in the management of protected areas which could hide relevant tendencies in CEG arrangements.

Considering ecological nodes, identifying N2000 sites where selected LIFE-NAT projects are implemented is required to identify protected habitats constituting the HN. To understand what protected habitats compose the selected N2000 sites, we use information retrieved from the N2000 database provided by the European Environment Agency (https://www.eea.europa.eu/data-260and-maps/data/natura-12). Additionally, we classify habitats following EUNIS classification (https://eunis.eea.europa.eu/habitats.jsp), distinguishing marine habitats, coastal habitats, freshwater habitats, heaths and scrubs habitats, grassland habitats, bogs, mires, fens habitats, rocky habitats, and forest habitats.

Consequently, we created a new database with information related to selected LIFE-NAT projects ("Projects section"), every beneficiary composing each project’s partnerships ("Beneficiaries section"), every N2000 site involved in projects ("N2000 section"), and every protected habitat composing the N2000 site ("Habitat section").

Social and ecological nodes are then connected through edges following criteria theorized during the network design phase, highlighting social-to-social, social-ecological, and ecological-to-ecological relations (see Table 1 of the article).

Information not reported in the previously cited sources, like the typology and scale of actors and the habitat classification, is retrieved through partners’ websites (for identifying type and level) and in the EUNIS (European Union Nature Information System) website.

SEN statistical analysis - ERGM

Networks are analyzed through Social Network Analysis (SNA). Relationships are analyzed through different approaches due to the nature of ties composing networks. For the specific case of social-ecological relationships, we use single-layer (i.e., allows only one single type of tie in the network) and multilevel (i.e., enables multiple kinds and quantities of edges within and between layers) approaches (Sayles et al., 2019). In particular, the PN and HN single-layer networks. Conversely, the SEN is a multilevel network.

Due to the irrationality of assuming independence between ties composing networks, which makes it impossible to use standard statistical methods, we use Exponential Random Graph Models (ERGM) (Lusher et al., 2013; Wang et al., 2013).

ERGMs are the principal approach used to model networks. They consider the presence or absence of network ties from which structural configurations emerge, reflecting behaviors or tendencies of the system we are analyzing (Lusher et al., 2013). As with every statistical model, ERGMs can make inferences about patterns characterizing the analyzed network, indicating if there are more or fewer observed structures in the network than expected by chance (Lusher et al., 2013; Wang et al., 2013). In other words, models can verify the presence or absence of tendencies in making relationships by analyzing sub-graph configurations in the studied network. Specifically, ERGMs can infer if a specific network configuration is significantly more present or absent than expected, comparing the observed network with all its possible rearrangements (Lusher et al., 2013). For example, suppose a protected area is managed by actors who collaborate. In that case, ERGMs tend to have triadic closure between two social nodes and one ecological node, as Bodin et al. (2016) detected. Additionally, ERGMs allow for the analysis of covariates to deepen the analysis, considering the endogenous structure and exogenous patterns determined by the specific characteristics of nodes, e.g., attributes that classify nodes composing the network (Lusher et al., 2013).

Models development. To verify research hypotheses, we develop three separated models referring to the three networks at the bases of this study (i.e., PN, SEN, HN) and identify specific network configurations able to detect tendencies representing behaviors expected by research hypotheses (tab.A1). Model 1 verifies H1, model 2 verifies H2 and H3, model 3 verifies H4.

For model 1, we use the *ergm package* inside the *statnet package* in *R software* (Krivitsky et al., 2021). Model 2, which deals with a multilevel network (i.e., SEN), is developed using *Pnet ® software* (Wang et al., 2013). Model 3, which deals with a weighted single-layer network, is developed using *ergm.count, ergm.rank, latentnet packages* inside *statnet package* in *R software* (Krivitsky et al., 2012).

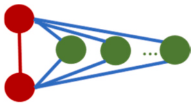
See Table A1.

Specifically, the three models are constituted by multiple network statistics (tab.A2), which expand the analysis of configurations beyond the main configuration required to verify the hypotheses. In this way, it is possible to deepen tendencies and arrangements of the CEG stimulated by LIFE-NAT projects, which could help explain if and why hypotheses are verified. Definitions of network statistics are reported in Table 3 of the article.

See Table A2.

We verify the presence or absence of multi-actor and multilevel collaborations in LIFE-NAT projects (H1) by analyzing LIFE-NAT partnerships represented through the PN. First, we make an ERGM model composed of the network statistics: “Edges,” “Nodematch_level,” “Nodematch_type,” “Gwdegree” (Krivitsky et al., 2021). Then, we create an ERGM model helpful to address H2 and H3 by studying endogenous

Table A1
Network configurations representing research hypotheses of this study.

Hypothesis	Configuration
H1 **LIFE-NAT projects promote social collaborations between partners able to concretize multilevel and multi-actor governance**	
H2 **A specific N2000 site represents a well-defined contextual setting for multiple collaborations determined by multiple LIFE-NAT projects.**	
H3 **LIFE-NAT projects act mainly in N2000 sites that are ecologically connected through ecological corridors.**	
H4 **LIFE-NAT projects stimulate synergic social collaborations among actors and initiatives that implement actions across different habitats.**	

🔴	Social node
🟢	Ecological node
—	Social relation
—	Ecological relation
—	Social-Ecological relation
a, b	Nodes attributes

Table A2
Network statistics used in models.

Model 1	Model 2	Model 3
Edges	AEdge	Sum
Nodematch_level	BEdge	Nodematch. sum.HABITAT, diff=TRUE
Nodematch_type	XEdge	Transitiveweights.min.max.min
Gwdegree	ATXAX	
	ATXBX	

network statistics to verify the presence or absence of structural configurations (Wang et al., 2013). The model is composed of the following network statistics reported in the Table 3: “AEdges,” “BEdges,” “XEdges, ” “ATXAX,” “ATXBX.” Specifically, for H2 purposes, we use the ATXAX statistic, and for H3 purposes, the ATXBX statistic (Table 2). Finally, we verify the presence of synergic social collaborations between projects acting across different habitats (H4) through the HN, creating an ERGM-weighted model (Krivitsky, 2012) composed of network statistics: “Sum,” “Nodematch.sum.habitat” and “Transitiveweights.min.max.min” (Table 3).

Finally, the models need to be tested to verify their stability and goodness of fit.

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