Report on the drivers and barriers to the provision of biodiversity and ES and the propagation of costs and benefits throughout the agri-food system

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Deliverable Description & Contributors

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- **Work package leader**: Claudio Petucco (LIST)
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- **Nature of deliverable**: Report
- **Dissemination level**: Public

- **Deliverable description:** This report will identify drivers and barriers of biodiversity sensitive farming systems for the provision of biodiversity and ES (in coordination with task 7.3), and the propagation on benefits and costs through the agri-food systems, using the insights derived from qualitative models of socio-ecological networks representing European agricultural systems, and pertubation analysis to identify the system dynamics in complex networks (Task 7.2).

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1. Background to the FRAMEwork project

1.1 FRAMEwork Project Executive Summary

Biodiversity is essential for agroecosystem resilience, sustainability, and long-term food security. Traditionally, management for short-term economic returns has taken priority over management for the environment. Current mechanisms for compensating and encouraging farmers to apply biodiversity sensitive management strategies are often inefficient, being applied at individual farm rather than landscape level, and tend to be generic solutions, imposed from the top down at an EU or national level. Monitoring is rarely carried out and there is therefore little scope for evaluating the success of strategies in achieving improvements to farmland biodiversity.

The FRAMEwork project has been designed and develop a novel alternative to this called the **FRAMEwork System for Biodiversity Sensitive Farming** to enable the transition of EU farming systems to a position where they can conserve biodiversity and benefit from the enhancement of ecosystem services, while mitigating agronomic or economic risks. The FRAMEwork System combines the following elements:

- **Advanced Farmer Clusters** – local farmer groups working as a collective to deliver landscape scale management, supported by a Cluster Facilitator with expertise in agriculture and the environment, and linked to a local Cluster Stakeholder Group to inform and promote policy and practice, organised into regional, national, and international networks.
- **Technical Resource** – technical specialists associated with the regional, national, international networks to provide technical information, methods, and tools to support agrobiodiversity monitoring, management and policy including the dedicated DSTs – FRAMEselect and FRAMEtest.
- **Scientific Innovation** – researchers associated with regional, national, international networks to provide knowledge on the ecology, sociology and economics that underpins the functioning of sustainable agricultural systems.
- **Citizen Observatory and Information Hub** – an open access platform to support FRAMEwork networks, sharing activities, information, data and resources between farmers, scientists, policy makers, and citizens.

The FRAMEwork project designs, builds, tests, and deploys a prototype of the FRAMEwork System for Biodiversity Sensitive Farming and works with 3 concepts important to the success and delivery of the project: (i) promoting collective landscape management; (ii) applying the approach across a diversity of European farming systems; and (iii) understanding and supporting the social and ecological change associated with a transition to biodiversity sensitive farming.

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1.2 Project Partners

No	Participant organisation name	Type	Country
1*	The James Hutton Institute (HUTTON)	Research Inst	UK
	Game and Wildlife Conservation Trust (GWCT)	Non-profit	UK
3	Groupe de Recherche en Agriculture Biologique (GRAB)	Non-profit	FR
4	Universitaet fuer Bodenkultur Wien (BOKU)	University	AT
5	Eesti Maaulikool (EMU)	University	EE
6	Hoehere Bundeslehr- und Forschungsanstalt fuer Landwirtschaft Raumberg-Gumpenstein (AREC)	Research Inst	AT
7	Fundacion Artemisan (ARTEMISAN)	Non-profit	ES
8	Scuola Superiore di Studi Universitari e di Perfezionamento Sant'anna (SSSA)	University	IT
9	The University of Hertfordshire Higher Education Corporation (UNI OF HERTS)	University	UK
10	Centro de Investigacion Ecologica Yaplicaciones Forestales Consorcio (CREAF)	University	ES
11	Institut National de la Recherche Agronomique (INRA)	Research Inst	FR
12	Internationales Institut fuer Angewandte Systemanalyse (IIASA)	Research Inst	AT
13	Universiteit van Amsterdam (UvA)	University	NL
14	Luxembourg Institute of Science and Technology (LIST)	Research Inst	LU
15	Universitaet Osnabrueck (UOS)	University	DE
16	Taskscape Associates Limited (TAL)	SME	UK
17	Ceska Zemedelska Univerzita v Praze (CULS)	University	CZ
18	Nordisk Fond for Miljo og Udvikling (NORDECO)	SME	DK

*Coordinating institution

1.3 Purpose of the report

Using a social-ecological network approach the aim is to apply a systems lens to identify agroecosystem elements that can potentially be drivers and/or barriers to on- farm biodiversity conservation and ultimately ecosystem service provision. This deliverable report highlights the application of the network approach to characterising agroecosystems and shares the relative importance of various system elements (nodes) and the associated implications for management, biodiversity conservation, ecosystem service provision and policy.

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2. Executive Summary

This report examines the complex dynamics of biodiversity conservation and ecosystem service provision across three distinct European agricultural systems: Scotland's arable systems, Italian olive groves, and Luxembourgish orchards. The study employs a social-ecological network (SEN) analysis to explore the interactions between ecological elements, social actors, and farming practices. By focusing on the drivers and barriers to biodiversity-sensitive farming, the report aims to inform policies that support sustainable agriculture while enhancing ecosystem resilience. It is based on several key research questions. These include identifying the ecological and social practices that shape agricultural systems, understanding which components are critical for delivering ecosystem services, and investigating how management decisions are influenced by social actors and external drivers. The study also seeks to evaluate how different farming practices, such as the implementation of flower strips in Scotland, livestock grazing in Luxembourg orchards, and olive grove management in Italy, contribute to biodiversity conservation or loss. To address these questions, the research team employed social-ecological network analysis, a method that visualises the relationships between ecological entities, ecosystem services, management practices, and stakeholders. Data for the analysis were collected using mixed methods, including literature reviews, expert interviews, field surveys, and workshops with farmers and stakeholders. These inputs helped construct multilayer networks for each farming system, revealing the complexity of interactions between different components.

The study identified nodes in each agroecosystem and categorised them into five layers: ecological entities (e.g. crops, livestock, and soil organisms), ecosystem services (such as pollination and nutrient cycling), ecological processes, management practices, and stressors (like pesticide use). Using network metrics including degree centrality and eigenvector centrality, the report identified the most influential nodes within each system. These were often the farmers themselves and the ecological processes underpinning ecosystem services. Flower strips in the arable fields of Scotland, have the potential to enhance biodiversity by supporting pollinators and natural pest control agents but at a landscape scale the actual outcomes depend on context-specific factors. In Luxembourg, livestock grazing in orchards presented both opportunities and risks: while it helped control weeds and supported certain ecosystem services, overgrazing posed threats to soil health through soil compaction. Meanwhile, in Italy, economic pressures contribute to the rise in the abandonment of olive groves, triggering a cascade of negative ecological impacts, including soil erosion, habitat degradation, and increased fire risk. The study also employed Causal Loop Diagrams (CLDs) to further explore the drivers of biodiversity loss in each system. These highlighted how management practices, such as grazing intensity or pesticide use, can either mitigate or exacerbate biodiversity loss.

One of the report's key conclusions is that while the challenges faced by each farming system are distinct, all three regions demonstrate the central importance of farmers as stewards of biodiversity through various management actions. However, farmers' ability to adopt biodiversity-sensitive practices is heavily influenced by social and policy factors, such as financial incentives, market pressures, and access to technical knowledge. Therefore, the report emphasises the need for a more integrated approach to agricultural management, involving stronger collaboration between farmers, policymakers, and environmental organisations.

For the policy recommendations, the report suggests the need for landscape-scale management approaches that recognise the interconnected nature of agricultural and ecological systems. Policies

could also tailor biodiversity initiatives to specific ecological and social contexts, rather than applying one-size-fits-all approaches.

3. Introduction and background

Biodiversity sensitive farming is increasingly becoming a popular approach for ensuring the sustainability and resilience of global agricultural systems. As the world population continues to grow, and demand for food increases, there is an urgent need for food production strategies that cater for both ecological integrity and food security. Most farming systems are focussed on yields and profit, at the expense of biodiversity loss, habitat degradation, and ecosystem disruption. In contrast, biodiversity sensitive farming emphasises the integration of agricultural productivity with conservation efforts, aiming to maintain and even enhance biodiversity within agricultural landscapes (Power, 2010; Tscharntke et al., 2012). This kind of farming is even more important in the face of other global challenges like climate change (Duru et al., 2015).

At the heart of biodiversity sensitive farming lies the recognition that agriculture depends on a wide array of ecosystem services. Services like pollination, pest control, soil formation, and nutrient cycling are underpinned by diverse biological communities. Maintaining such diversity can buffer agricultural systems against shocks such as pest outbreaks and changing weather patterns (Kremen & Miles, 2012; Bommarco et al., 2013). However, realising the full potential of biodiversity within agricultural systems requires a nuanced understanding of how these systems function. Agricultural systems mapping is a useful approach for this purpose. It helps to conceptualise and visualise the complex relationships between farming practices, biodiversity, and ecosystem services, thereby offering critical insights into how these factors can deliver more sustainable outcomes (Tittonell, 2014, Pretty et al., 2010).

Agricultural systems are inherently complex, with multiple interacting components including crops, livestock, soil, water, and the broader ecological context in which they operate. Effective integration of biodiversity sensitive practices into these systems hinges on a clear understanding of their structure and dynamics. Through mapping, it is possible to identify elements of high ecological value, for example such as hedgerows or wetlands, which serve as important habitats for beneficial species like pollinators and predators of crop pests (Pywell et al., 2015). Simultaneously, mapping can help highlight management actions (e.g. pesticide use) that exert of pressure on biodiversity. By understanding these interactions, farmers with the appropriate policy/ institutional support can implement management practices that not only conserve biodiversity but also enhance ecosystem services critical to agriculture (Tscharntke et al., 2012). In addition to ecological factors, mapping agricultural systems can help identify external drivers like climate change, policies and market dynamics which may have both direct and indirect influence on the sustainability of biodiversity sensitive practices. For example, mapping can inform decisions on the adaption of farm management in response to shifting climate patterns or market demands for more sustainably produced food (Duru et al., 2015). In this way, agricultural systems mapping not only supports biodiversity conservation but also enhances the adaptability and resilience of farming systems.

Most systems mapping tools for understanding how biodiversity functions within agricultural systems, often focus on individual components, such as land use or species distributions (Harrison, et al, 2014, Bennet et al 2009)). To gain a more comprehensive understanding of the interactions between farming practices, biodiversity, and ecosystem services, researchers are increasingly turning to social-ecological network analysis (Bodin & Tengo, 2012, Sayles, & Baggio, 2017). This method provides a systems level view of the entire socio ecological system, showing the complex interplay between ecological and social components.

Social-ecological networks are analytical tools used to visualise and study the relationships between ecological elements (species, ecosystems) and social elements (farmers, institutions, markets in agricultural systems (Sayles & Baggio, 2017). These networks consist of nodes, representing different components of the system, and edges, which depict the interactions or dependencies between these nodes (e.g. pollination services, nutrient flows, or economic exchanges) (Ostrom, 2009). Constructing a social-ecological network involves gathering data from various sources, including field surveys, ecological monitoring, farmer interviews, literature reviews, agricultural reports, and market data (Bodin & Tengo, 2012). Once constructed, the network can be analysed to identify key nodes or relationships that play a critical role in the system. For example, certain species might act as keystone species, providing vital ecosystem services such as pollination or pest control (Kremen et al., 2018). Identifying these keystone nodes enables targeted conservation efforts that can enhance the overall resilience and functionality of the agricultural system.

Social-ecological networks are particularly valuable for identifying systemwide drivers of biodiversity loss, the associated consequences and the effect of implementing biodiversity sensitive farming practices. For instance, network analysis might reveal how agri-environment schemes influence farmers decisions to align their management activities with biodiversity-friendly practices (Pretty et al., 2010). Understanding these social dynamics is crucial for designing policies and interventions that promote biodiversity conservation while supporting farmers livelihoods. Furthermore, social-ecological networks can provide insights into the costs and benefits of adopting biodiversity-sensitive practices by mapping the flow of ecosystem services within the agricultural system. For example, network analysis can reveal how changes in land management affect the provision of pollination, water purification, or soil fertility services, and how these services, in turn, influence agricultural productivity (Sayles & Baggio, 2017). By highlighting these connections, social-ecological networks offer a powerful tool for unlocking the full potential of biodiversity-sensitive farming.

Biodiversity-sensitive farming represents a critical shift toward more sustainable and resilient agricultural systems. By integrating biodiversity into farming landscapes, these systems can enhance ecosystem services, reduce dependency on external inputs, and improve adaptability to environmental change. Agricultural systems mapping and social-ecological network analysis provide essential tools for understanding the complex relationships between farming practices, biodiversity, and ecosystem services. For these reasons we conducted a study in 3 farming systems to with the following questions guiding the research:

1. What are the key ecological, social and management practices that shape the agricultural network structure?
2. What are the most important ecological entities for the delivery of ecosystem services from farming systems?

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3. What are the important the social actors/processes for potentially driving or hindering decisions to implement specific management practices?
4. Across the three farmer clusters, what are the main cause and effects of biodiversity loss and how do can specific management practices halt biodiversity loss?
    a. Scottish cluster- Effect of implementing flower strips (field margins) on farm biodiversity
    b. Italy cluster – The causes of olive grove abandonment and their implications on biodiversity and ecosystem service provision.
    c. Luxembourg cluster- Effect of grazing livestock in apple and pear orchards

The objectives

- To identify and map key ecological, social and management practices that shape the agricultural network structure
- To identify the most important ecological entities for delivery of ecosystem services and the key stakeholders/processes for potentially driving or hindering the decision making about management practices
- To identify the causes and effects of biodiversity loss and assess the implications specific management practices on farm biodiversity, productivity and ecosystem services

4. Study sites (the case studies)

We selected three farmer clusters for the social-ecological network analysis: Buchan in Scotland, Born in Luxembourg, and Val Graziosa in Italy. These locations were chosen to capture a wide range of geographical, agricultural, and cultural differences. The clusters cover a broad geographical stretch, from northern Scotland down through central Europe in Luxembourg, and finally reaching southern Italy (Figure 1) This allowed us to study diverse regions with distinct environmental conditions. The selected areas also reflect different practices—arable farming, olive groves, and apple and pear orchards. These clusters offer a foundation for analysis, giving us valuable insights into varied farming techniques and social conditions. The methods outlined in this report can be applied to other farmer clusters in future research.

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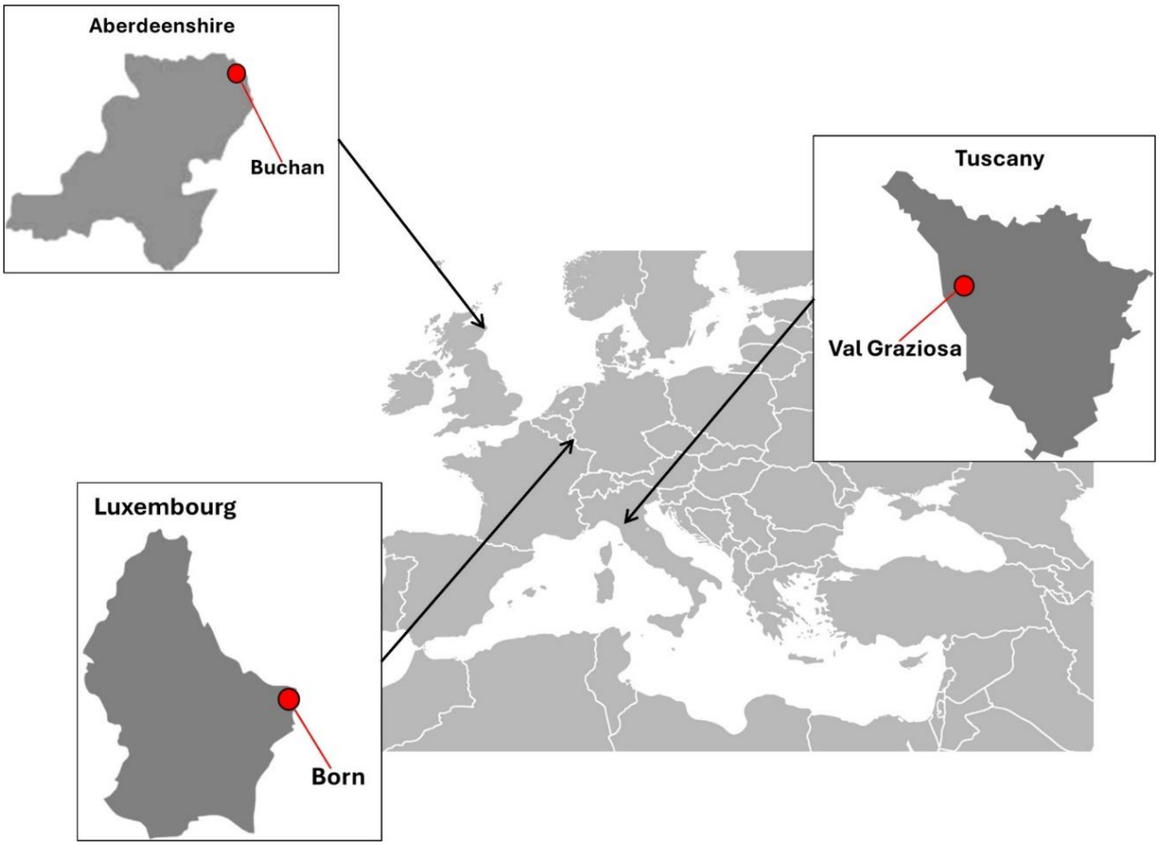

Figure 1. The locations of the clusters-study sites.

4.1 Buchan, Scotland

Buchan is in the Northeast of Scotland, within the Aberdeenshire region. It is a coastal area, bordered by the North Sea, with a landscape characterised by low hills and predominantly rural terrain (Hall, 2021). The region has a temperate maritime climate, bringing cool summers, mild winters, and consistent rainfall throughout the year (Köppen, 1936). However, its proximity to the North Sea makes strong winds a frequent feature of the area (Coutts & Martín Aranda, 1963). Buchan is largely agricultural, with extensive fields of barley and wheat, and grasslands that support grazing livestock, particularly sheep and cattle (Agricultural Census Branch, 2023). Both arable and livestock farming dominate the land use, with small woodlands interspersed across the landscape (Scottish Government Rural Payments and Services, 2000-2022). In some of the coastal towns, the fishing industry remains central to the local economy (Brookfield et al., 2005). Additionally, the region benefits from the offshore oil and gas fields in the North Sea (Allan et al., 2020), alongside some forestry and small-scale food processing industries (Dalton, 2016). Buchan is sparsely populated, with its inhabitants spread across small towns, villages, and individual farms (Scotland's census, 2022). Peterhead, the largest town, acts as the region's economic hub (Brookfield et al., 2005), while the surrounding area remains largely rural with minimal suburban development (CEH, 2021). The natural environment is heavily influenced by agricultural activity (CEH, 2021). In areas not used for farming, native grasses and heathland plants like heather, gorse, and broom thrive, while woodlands consist primarily of Scots pine, birch, oak, and rowan trees (Forster and Green, 1985). Along the coastline, resilient plants such as sea thrift and marram grass adapt to the salty conditions (Sterry & Cleave, 2022). Wetlands and

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moorlands in the area support species like sphagnum moss, cotton grass, and rushes (Freeman, 2018). Buchan is also home to a range of wildlife, including red and roe deer, badgers, foxes, and rabbits (van Zyl, 2009). The area's birdlife includes species such as puffins, gannets, and guillemots nesting along the coast, while birds of prey, including golden eagles and peregrine falcons, are present inland (Harrap, 2015). The coastal waters are habitats for marine species like grey seals and dolphins, and the region's rivers and streams support populations of salmon and trout (Plass, 2013; van Zyl, 2009). Buchan faces several environmental challenges, many of which are related to intensive farming practices.

Soil degradation, caused by erosion and nutrient depletion, is a significant concern, while the use of fertilisers and pesticides has impacted water quality (Hooda et al., 2000; Skinner et al., 1997). The region is also vulnerable to the effects of climate change, including rising sea levels and more frequent extreme weather events, which exacerbate flooding and coastal erosion, particularly in low-lying areas (Werritty & Sugden, 2012). Biodiversity loss, driven by habitat fragmentation from farming and development, poses further risks to the region's native species (Pakeman et al., 2023). In addition, the fishing and oil and gas industries present ongoing risks of marine pollution, including overfishing, waste, and potential oil spills (Allan et al., 2020; Sandison et al., 2021). The Buchan Farmer Cluster focuses on improving biodiversity and soil health across a large geographical area. Farmers in this cluster work together to implement practices that enhance ecological health, benefiting both their farming operations and the wider environment. These practices include no till farming, the establishment of field margins, and the planting of cover crops. The cluster also serves as an important social activity, reducing the isolation often experienced in farming by providing opportunities for networking and mutual support.

4.2 Born, Luxembourg

Born, part of the municipality of Rosport-Mompach, located in the Sauer (Sûre) River valley, which forms part of the natural border between Luxembourg and Germany. The region's landscape marked by low hills and fertile plains (Cammeraat, 2006). The area experiences a temperate climate, with mild temperatures and moderate rainfall throughout the year. Summers are generally warm, while winters remain cool with occasional frost (Köppen, 1936). The surrounding landscape is a mix of agricultural fields, vineyards, and forests (EEA, 2018). The region's fertile soil supports a variety of crops, including cereals, stockfeed, vegetables, grapevines, and fruit orchards (Gohin & Latruffe, 2006; Weichold, 2022). The area is moderately populated, characterised by small villages and isolated farms. Despite this, it is near urban centres (EEA, 2018). Agriculture, including viticulture, crop farming, dairy, and fruit production, remains the main industry. In recent years, tourism has become increasingly important, while light manufacturing and services also contribute to the region's development (Uppenberg and Strauss, 2010; Danescu, 2010) The flora around Born is heavily influenced by agriculture and consists of a mix of forests, agricultural fields, and riverbank vegetation along the Sauer River. The forests are primarily composed of oak, beech, and hornbeam trees, with an understory of shrubs and wildflowers. In less cultivated areas, wildflowers such as daisies and buttercups are common (Tackenberg, 2019). The region's forests and farmlands are home to species such as roe deer, wild boar, foxes, hedgehogs, storks, kestrels, and owls. The Sauer River supports a variety of aquatic life, including fish species such as trout and pike, insects and amphibians (iNaturalist, 2024). The environment around Born faces several challenges. Agricultural runoff, particularly from

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fertilisers and pesticides, poses a threat to the Sauer River's water quality and aquatic ecosystems (Salvia-Castellví et al., 2005).

Periodic droughts, likely linked to climate change, can also strain the region's water supply, particularly in rural areas where agriculture relies heavily on irrigation (Zoccatelli et al., 2024). Intensive farming practices and changes in land use have contributed to habitat loss, affecting biodiversity (Almenar et al., 2019). Pollution, both from industrial discharges and household waste, further endangers the Sauer River's ecosystems (Aurich et al., 2023). The Born Farmer Cluster involves farmers committed to addressing biodiversity loss and promoting sustainable land management practices. This cluster emphasises the importance of joint action and community involvement. Practices such as agroforestry related to apple production and grazing are commonly implemented. The cluster leverages citizen science activities to gather data and raise awareness about biodiversity conservation, aiming to achieve significant environmental benefits at a landscape scale.

4.3 Val Graziosa, Italy

Val Graziosa is in the Tuscany region of Italy, near the city of Pisa. It lies beneath the Monte Pisano Mountain range and is characterised by moderately steep slopes and a flat valley floor (Coltorti et al., 2017). The region experiences a typical Mediterranean climate, featuring hot, dry summers and mild, wet winters (Köppen, 1936). The landscape of Val Graziosa is predominantly shaped by agricultural activities. Olive groves dominate the valley, with the higher parts of the slopes covered in Mediterranean scrub and forests (EEA, 2018). On the valley floor, more intensive agriculture is practiced, while traditional, less mechanised farming methods persist in the hillside areas (Venturi et al., 2017). Olive cultivation and olive oil production are central to the local economy (Guarino et al., 2019). The valley also supports vineyard cultivation, although to a lesser extent. Livestock grazing is also a common practice in the area (Caballero et al., 2009). The valley's natural environment is marked by Mediterranean flora. Cypress trees, as well as shrubs such as rosemary and thyme, are common. The surrounding hills support forests of oak, chestnut, and pine, while wildflowers like poppies and daisies flourish in the spring (Gardener, 2020). The fauna of Val Graziosa includes a variety of species, such as wild boar, foxes, hares, and hedgehogs and variety of reptiles. The avian population includes species like kestrels, buzzards, and hoopoes (Blondel & Aronson, 1999). The valley encompasses the municipality of Calci, which consists of several small villages and hamlets surrounding the main settlement of La Pieve. The valley's proximity to the metropolitan area of Pisa makes it a peri-urban environment. Despite its agricultural and ecological richness, Val Graziosa faces several environmental challenges. The hilly terrain makes the region particularly vulnerable to soil erosion where farming practices can exacerbate land degradation and lead to landslides (Märker et al., 2008). Additionally, agricultural expansion and urbanisation has resulted in biodiversity loss, as natural habitats have become fragmented, and the use of pesticides poses a threat to pollinators (Falcucci et al., 2007; Ruiz-Martinez et al., 2020). Water shortages are another significant concern, particularly during the summer months when the demand for irrigation is high (Venturi et al., 2014). The risk of wildfires during the dry season further intensifies these environmental pressures, damaging both natural and semi-natural habitats and agricultural land (Chastain and Islar, 2024). The Val Graziosa Farmer Cluster is dedicated to preserving and studying biodiversity within the region. Farmers in this cluster collaborate to find innovative solutions and better understand the ecological balances surrounding their farms. Agricultural practices include olive orchards, and they focus on integrated pest management and organic farming. The cluster is composed by a mixture of professionals and hobby famers. Since the Italian law does not allow the hobby farmers to sell their oil, which is for personal use only, the SEN analysis focuses only on the professional farmers.

5. Methodology

5.1 Network representation

Agroecosystems can be thought of as a network made up of different components, where each element whether it's plants, animals, people, or various biotic and abiotic processes acts as e a node in the system. The connections between these nodes, or the edges, represent the flow of impact, such as how nutrients cycle or energy transfers through the system. By mapping these interactions in a network, it becomes possible to visualise the way various parts interact and depend on one another. This approach helps us understand how each piece contributes or detracts to the overall health and resilience of the agroecosystem. The process of network creation included the development of a conceptual model, identification of nodes, validation of nodes by the cluster facilitators, identification of edges, and generation of matrices for further analyses (Figure 2).

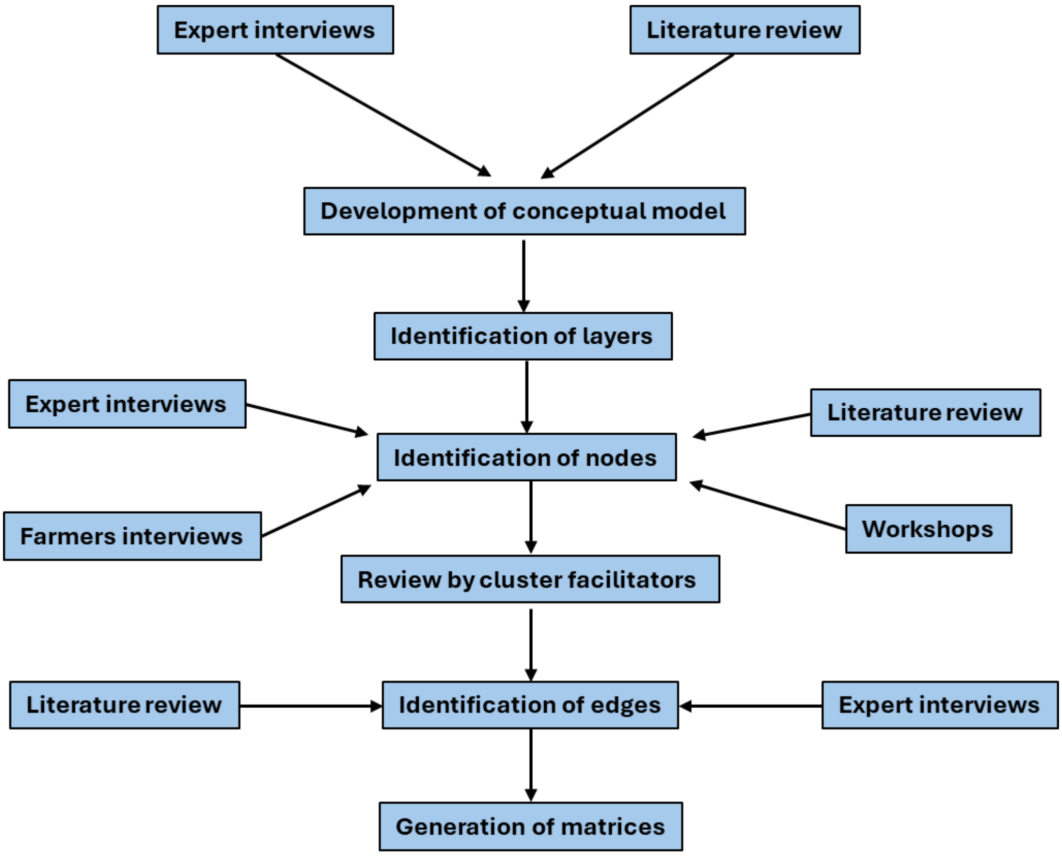

Figure 2. The workflow for the network construction.

5.1.1 Development of conceptual model

Through a careful review of existing research, we created a general network model of the system. This model helped us identify the key parts of the system (layers). These layers include ecological entities

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(such as plants and animals), ecological processes (like nutrient cycling or energy flow), the benefits that ecosystems provide to people (ecosystem services), the people and organisations involved (stakeholders), the ways ecosystems are managed (management practices), and the factors that cause harm to the system (stressors) (Table 1). We went on to determine rules to define how these influences flow (Figure 3). One key decision was that the overall direction of impact would flow in only one direction between the layers. This means that stressors, like pollution or habitat alteration, affect ecological entities (such as plants and animals), but those entities do not affect the stressors. Ecological entities interact with one another through ecological processes.

Ecological entities also provide ecosystem services which are then transferred to the stakeholders. The stakeholders determine the management practices. These management practices, in turn, influence the occurrence of stressors, which impact the ecological entities.

Table 1. The definition of the system elements

Name of layer	Description	References
Ecological entities	The various biophysical components of the ecosystem that interact with each other and their environment.	Castle et al., 2022 ; Caulfield et al., 2020 ; Gaba et al., 2014 ; Kumar Kohli et al., 2007 ; Pédèches et al., 2023 ; Shennan, 2008 ; Soga & Gaston, 2020 ; Zimmerer et al., 2022
Ecological processes	The various interactions and events that occur within the ecosystem, influencing the flow of energy, nutrients, and organism	Moraine et al., 2017 ; Pédèches et al., 2023 ; Shennan, 2008 ; Steinmetz et al., 2021
Ecosystem services	The benefits that humans derive from ecosystems.	Andersson et al., 2015, 2015 ; Castle et al., 2022 ; Cet al., 2015 ; Lomba et al., 2022 ; Moraine et al., 2017 ; Shennan, 2008 ; Soga & Gaston, 2020
Stakeholders	Individuals, groups, organisations, or institutions that play active roles in social interactions, shaping, influencing, or responding to social phenomena and processes.	Caulfield et al., 2020 ; Gallardo-López et al., 2021 ; Lescourret et al., 2015 ; Moraine et al., 2017 ; Pédèches et al., 2023 ; Soga & Gaston, 2020 ; Stojanovic et al., 2016
Management	Planning, organising, directing, and control of resources and activities to optimise agricultural production.	Caulfield et al., 2020 ; Felipe-Lucia et al., 2022 ; Gaba et al., 2014 ; Lescourret et al., 2015 ; Lomba et al., 2022
Stressors	Physical, biological, or chemical conditions that causes stress, strain or pressure on organisms, systems, or environments.	Tilman et al, 2002, Matson et al 1997, Foley, et al 2007, Giller et al 2009, Searchinger et al 2018, Deguines et al 2014

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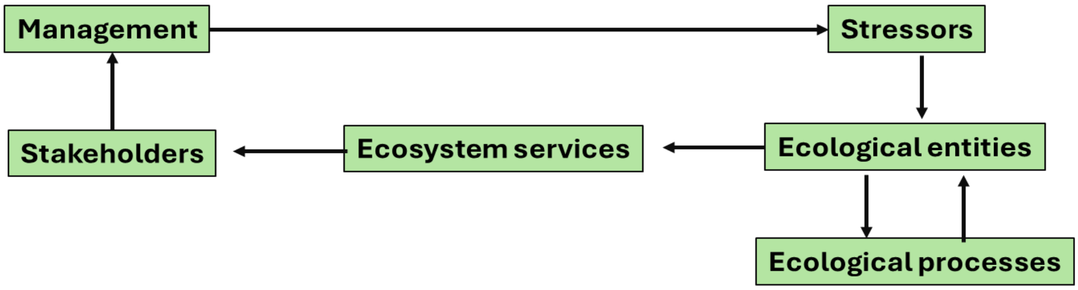

Figure 3. The conceptual model showing the 6 layers encompassing the system and their direction of relationship.

5.1.2 Identification of nodes

We applied mixed methods to identify the elements (nodes) that encompass the agroecosystem and its structure, including a literature review, expert interviews, workshops, and interviews with farmers. We focused on the processes and practices typical of agricultural systems in Scotland, England the EU (Grosinger et al., 2022; Perpiña Castillo et al., 2018; Steinmetz et al., 2021; Zimmerer et al., 2022). We then intentionally focused on the biodiversity-related components of the system and used the CICES classification (Haines-Young et al., 2018) for categorising the ecosystem services. Stakeholders were identified according to the services they provide to the farming system or the services/products they receive. The result was a universal list of nodes encompassing all the potential nodes in a European agroecosystem.

5.1.3 Validation of nodes by the cluster facilitators

Based on their understanding of the cluster's biophysical characteristics, biodiversity objectives, and stakeholders, the facilitator used a simple spreadsheet to mark the presence or absence of each node from the universal list of nodes created in Section 7.1.2. The facilitator used '1' to indicate presence and '0' to indicate absence. They were also authorised to add any nodes they felt were missing. From this, a list of nodes was generated for each cluster (Annex xiii).

5.1.4 Identification of edges

Through expert opinion and a literature review, the relationships between pairs of nodes with the potential to interact (meaning the nodes belong to two different layers connected in the conceptual model) were examined to determine whether a relationship exists and, if so, its nature. This study focused exclusively on direct relationships—interactions between nodes without intermediary agents. A comprehensive list of edges, along with detailed descriptions of the relationships and justifications for their occurrence, was created.

5.1.5 Generation of matrices

Based on the lists of nodes and the identification of where edges occur, connection matrices were created. These matrices are essentially binary adjacency tables, with the names of all the nodes in the system placed along both the X and Y axes. At the intersection of each pair of nodes, a number is placed, indicating whether an edge exists (1) or does not exist (0) between them. Since the system was defined as unidirectional, the nodes on the X axis influence those on the Y axis, but not the other

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way around. Based on the validation of the nodes in each cluster (Section 7.1.3), three matrices were generated, each representing the unique network of its respective cluster. These resulting matrices were employed for network visualization and subsequent structural analysis (Section 7.2).

5.2 Network analysis

A comprehensive network analysis was conducted to understand the structure and dynamics of the different clusters. Our analysis focused on evaluating the centrality of nodes within each network to determine their relative importance, influence, and roles, enabling us to compare the various network structures of the clusters. We employed five centrality metrics: in degree, out degree, eigenvector, betweenness, and closeness (Borgatti and Brass, 2019).

5.2.1 In and Out Degree Centrality

Degree centrality measures the number of direct connections each node has within the network. This metric identifies nodes that are highly connected, indicating potential hubs of activity or influence. By quantifying these direct ties, we can assess the basic level of node connectivity, with higher degree centrality suggesting greater involvement or influence within the network. To capture the directionality of relationships, we separately calculated in-degree and out-degree centrality. In-degree centrality, also known as prestige centrality, measures the number of incoming connections to a node, identifying nodes that are frequently targeted or impacted by others. Out-degree centrality measures the number of outgoing connections from a node, indicating nodes that frequently target or impact other nodes.

5.2.2 Eigenvector Centrality

Eigenvector centrality was employed to assess the influence of nodes based not only on their direct connections but also on the centrality of the nodes they are connected to. This metric was particularly valuable for identifying nodes that are connected to other highly influential nodes, thereby amplifying their own importance in the network. Nodes with high eigenvector centrality were considered key influencers with potentially far-reaching impact across the network.

5.2.3 Betweenness Centrality

Betweenness centrality was calculated to determine the extent to which a node lies on the shortest paths between other nodes in the network. Nodes with high betweenness centrality were identified as critical intermediaries or brokers. This metric was crucial for understanding the nodes' roles in connecting otherwise disparate groups, thereby influencing the overall connectivity and cohesion of the network.

5.2.4 Closeness Centrality

Closeness centrality was used to evaluate how quickly a node can interact with all other nodes in the network, based on the shortest path distances. Nodes with high closeness centrality were identified as strategically positioned to efficiently reach and influence the entire network. This metric provided insights into the potential speed and effectiveness with which nodes could disseminate information or resources.

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The results from these centrality metrics were analysed to identify key nodes within the network, their roles, and their potential impact on network dynamics. By comparing the different centrality measures, we could differentiate between nodes that are well-connected, those that are influential due to their strategic position, and those that play a critical role in maintaining the network's overall structure and function. Utilising these centrality measures together provided a multi-dimensional view of the network's structure and dynamics. and enabled us to fully understand the roles of different nodes and make more informed conclusions about the network’s overall structure and function.

5.3 Construction of the Causal Loop Diagrams

Just like other farming systems, the three case studies reported are subject to various pressures that can lead to declines in biodiversity. This can include factors such as monoculture practices, pesticide use, habitat fragmentation, and climate change. To explore the implications of some management practices on biodiversity loss in these systems we used the causal loop diagram approach. For the Luxembourg and the Scottish systems, we used biodiversity loss as a reference mode to help understand the effects of different management practices (grazing livestock in orchards, flower strips in crop fields) as biodiversity-sensitive farming practices to reverse this trend. For the Italian cluster the reference mode is olive grove abandonment which is a trend that is growing over the years. We used the CLD to explore why this is the case and what the implications are for biodiversity. For the creation of the causal loop diagrams (CLD) we identified some variables that relate to the causes of problem (i.e. the reference mode) and the associated consequences. These variables (causes and consequences) were picked from the stressor nodes identified in the network construction above while the consequences were picked from ecosystem services and the ecological entities. We then used a combination of literature review and expert knowledge to capture the intricate cause-and-effect relationships within each system and to add other nodes that are linked to biodiversity loss.

For each farming system, a separate CLD was created, identifying key variables (nodes) and mapping causal relationships, including feedback loops. The diagrams provide a visual and conceptual framework to understand the causes of biodiversity loss and associated consequences and how specific management actions impact biodiversity dynamics. The results from the network analysis were then cross-referenced with the CLDs to examine the role of high-centrality nodes within the broader system and their implications for biodiversity management. This integration of CLDs and network analysis allows for a deeper understanding of key drivers in each system and informs targeted management strategies to enhance biodiversity outcomes.

6. Results

6.1 The agroecosystems nodes across the three clusters

Our analysis revealed noticeable differences in the composition of nodes across the three clusters we examined. In Buchan, we identified 119 nodes, made up of 16 ecological entities, 21 ecological processes, 31 ecosystem services, 21 management practices, 14 stakeholders, and 16 stressors. In contrast, Born had a slightly higher total of 124 nodes, consisting of 15 ecological entities, 21 ecological processes, 24 ecosystem services, 16 management practices, a substantially higher 43 stakeholders, and 5 stressors. Val Graziosa, on the other hand, had 100 nodes, with 10 ecological entities, 21 ecological processes, 19 ecosystem services, 10 management practices, 34 stakeholders, and 6

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stressors. Interestingly, the number of ecological processes remained consistent across all three regions, with each cluster recording 21 processes. This suggests that core processes are shared between all clusters. However, notable differences emerged when we looked at ecological entities, ecosystem services, management practices, stakeholders, and stressors. Buchan, for example, had the highest number of ecosystem services and stressors, but fewer stakeholders than Born, which had the most among the three. Val Graziosa, meanwhile, showed a simpler structure, with fewer entities, services, and stressors, though it still maintained a relatively high number of stakeholders. Buchan stood out with six unique ecosystem services, indicating that it benefits from ecological functioning not seen in the other regions. It also employs six unique management practices, reflecting a distinctive approach to managing its agroecosystem compared to Born and Val Graziosa. Despite having the fewest stakeholders overall, Buchan still identified six unique stakeholders, which suggests a system-specific network of actors at play. Additionally, Buchan faces nine unique stressors, highlighting localised environmental pressures not felt elsewhere. In addition, Buchan includes one ecological entity – aquatic flora and fauna, which is not shared with the other clusters. In Born, the stakeholder network is particularly distinctive, with 15 unique stakeholders, reflecting a highly localised and socially complex system involving diverse interests. Born also contends with one unique stressor, indicating that while many stressors are shared with other regions, some remain specific to this region. Val Graziosa, like Buchan, identified just one unique ecological entity, olive trees. The region uses five unique management practices, reflecting its own strategies to meet local agroecosystem needs. With 32 unique stakeholders, Val Graziosa, similar to Born, presents a socially complex system. Even though it faces fewer stressors overall, Val Graziosa still grapples with one stressor not observed in other regions.

6.2. Multilayer directed network layout

This section presents a graphical description of the three representative networks. The layouts of the three networks are depicted in Figure 4 - Figure 6, illustrating the interactions among the different entities of each multilayer network, i.e. Born, Val Graziosa, and Buchan. These networks have sizes (i.e. nodes) of 124, 110, and 120, respectively, and 967, 1568, and 1673 edges.

In these figures, nodes sizes are represented proportional to their importance as measured by the eigenvector centrality. The nodes in the graph are color-coded according to their layers, with the edges adopting the colour of the origin node to indicate the direction of influence. It is evident from the graphs that the clusters' farmers (i.e. Born- the orchard system, Val Graziosa - the Olive system and Buchan – mixed arable crop-livestock systems) occupy a central position within the network, acting as the most influential node based on eigenvector centrality and while they could be depicted as 'stakeholders', we isolated them in one unique type of layer to facilitate the analysis. The three graphs illustrate variations in network density, highlighting the interconnectivity of each system. In Born, the network is highly concentrated around key stakeholders and management nodes. In contrast, Val Graziosa shows a noticeable shift toward ecological nodes. Buchan presents a more balanced structure, with no single group dominating. In Born, ecological processes and entities are relatively underrepresented, suggesting a system more influenced by human activities. Conversely, Val Graziosa prioritises these ecological aspects. Buchan exhibits a more balanced network structure, where no single layer dominates.

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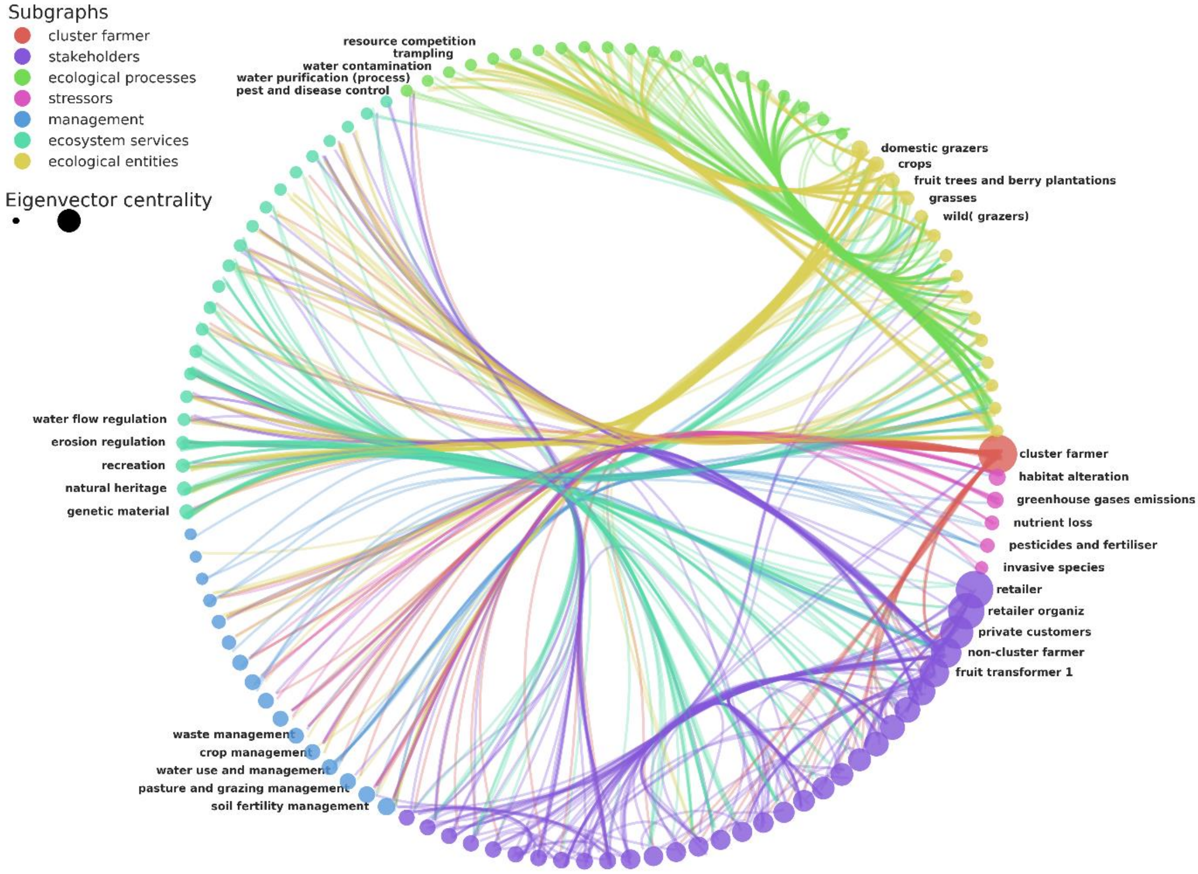

Figure 4. Directed network representing interactions among the different entities of the Born network. Edge colours represent the subgraph that originates the interaction (i.e. layers), and the node size is proportional to the eigenvector centrality of each node, a centrality measurement that indicates the importance of the node in the whole network. Only labels from the five more important nodes are visualised to avoid overloading the figure.

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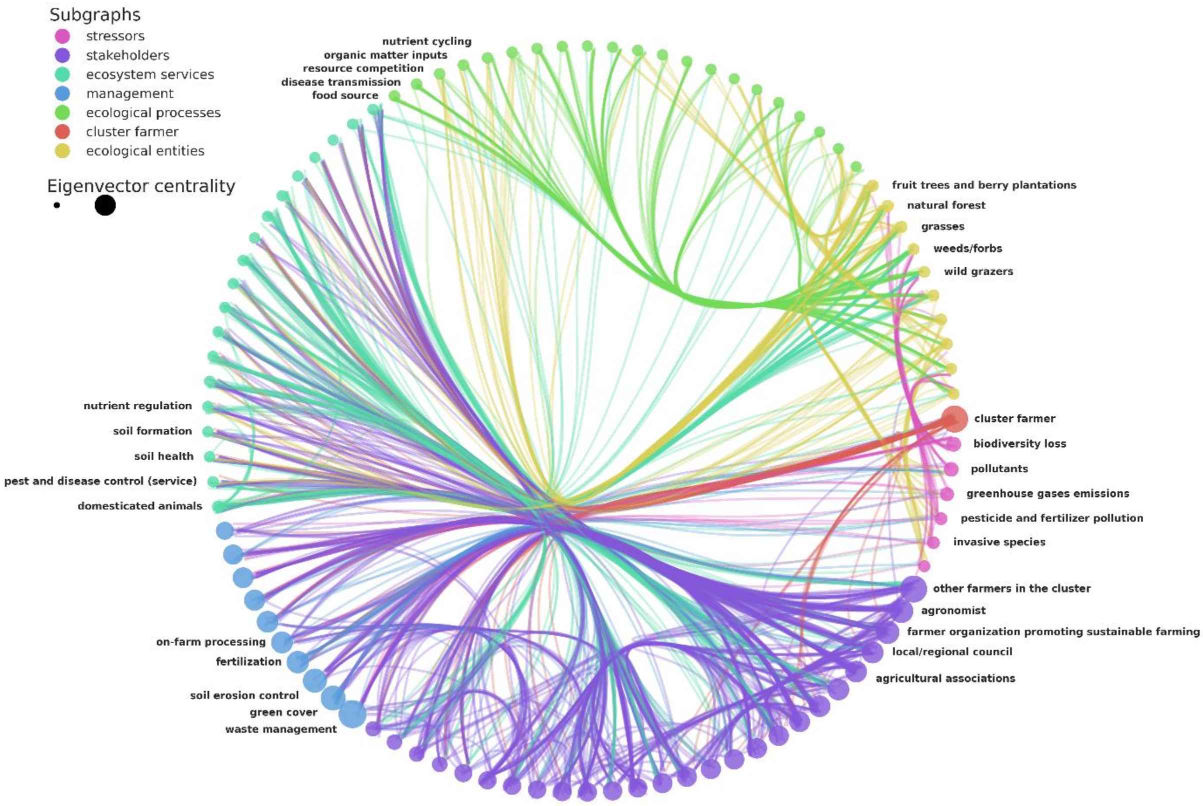

Figure 5. Directed network representing interactions among the different entities of the Val Graziosa network. Edge colours represent the subgraph that originates the interaction (i.e. layers), and the node size is proportional to the eigenvector centrality of each node, a centrality measurement that indicates the importance of the node in the whole network. Only labels from the five more important nodes are visualised to avoid overloading the figure.

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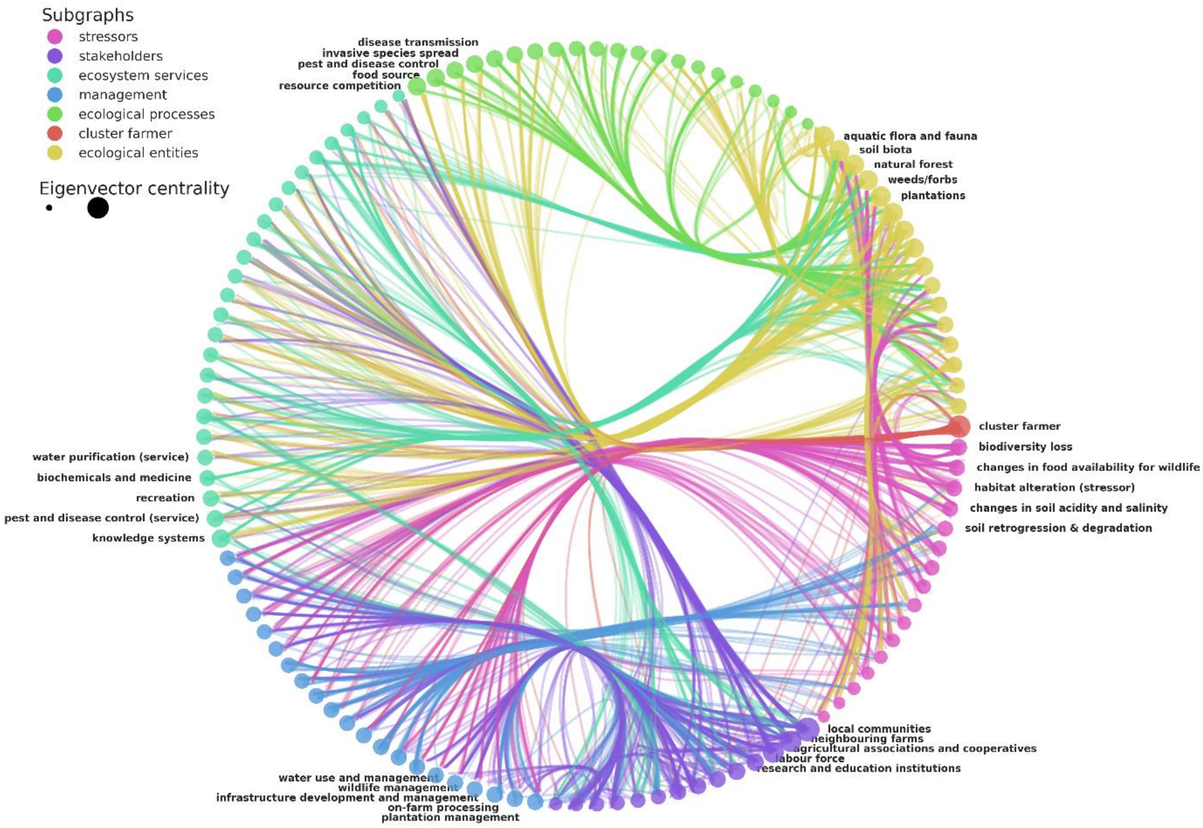

Figure 6. Directed network representing interactions among the different entities of the Buchan network. Edge colours represent the subgraph that originates the interaction (i.e. layers), and the node size is proportional to the eigenvector centrality of each node, a centrality measurement that indicates the importance of the node in the whole network. Only labels from the five more important nodes are visualised to avoid overloading the figure.

Differences in network density can be distinguished better when taking the stakeholder – management layers as example. Born contains few nodes with considerably high out-degree centrality (Figure 8), while in Buchan most of the stakeholder are connected similarly and no prominent stakeholder shows up (Figure 9). In a similar way, Figure 10 shows that, in Born, few ecosystem services nodes are highly connected, which contrasts with Val Graziosa (Figure 11), where ecosystem services are highly connected to the stakeholders, and they are also important nodes since they have a high out-degree centrality. A similar graphical description of the inter-layer interaction can be found in the annex.

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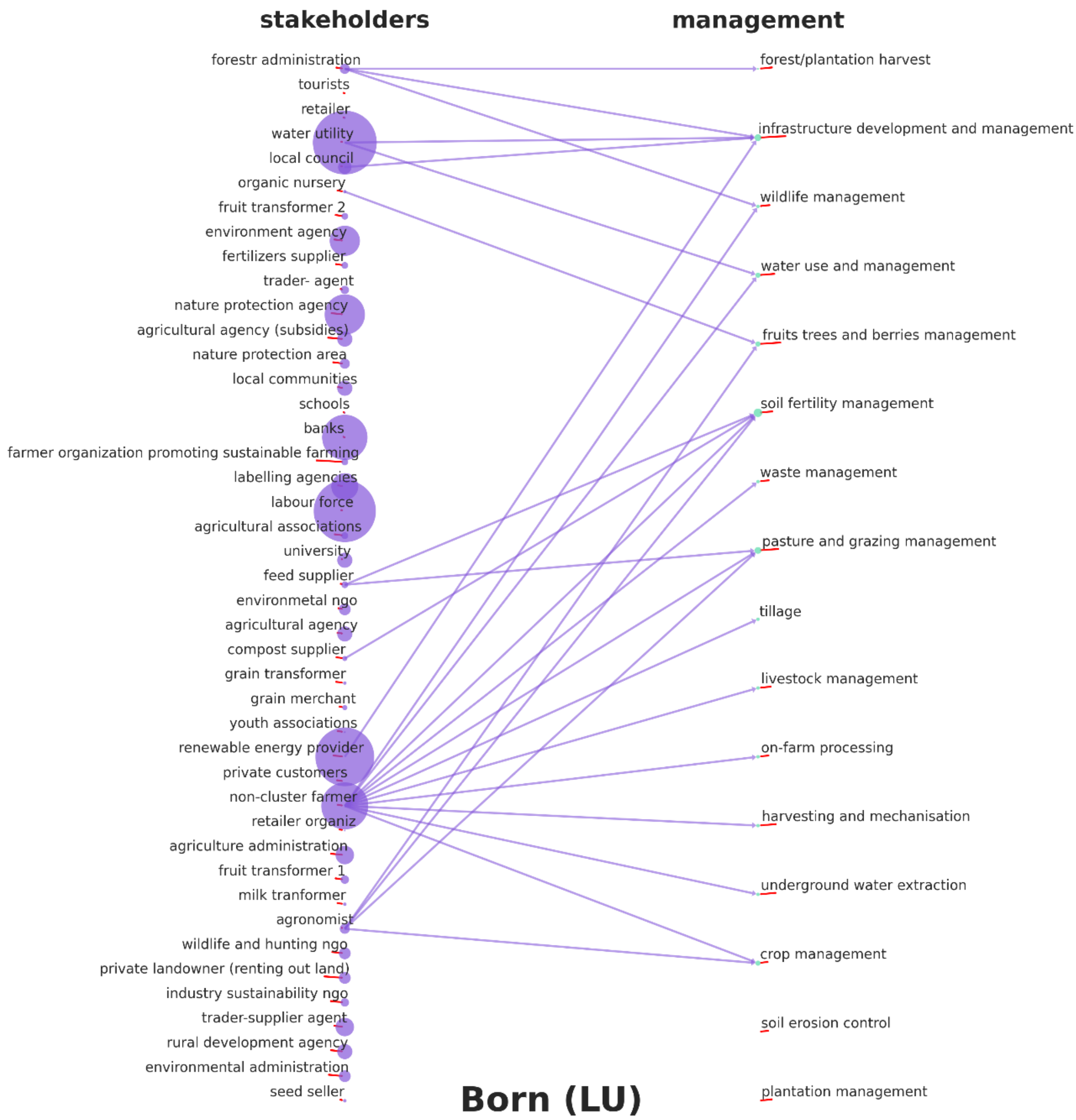

Figure 7. Directed interactions from the stakeholder to the management layer in Born. Nodes' size in the stakeholder's layer is proportional to their out-degree centrality, while in the management layer it is proportional to the in-degree centrality.

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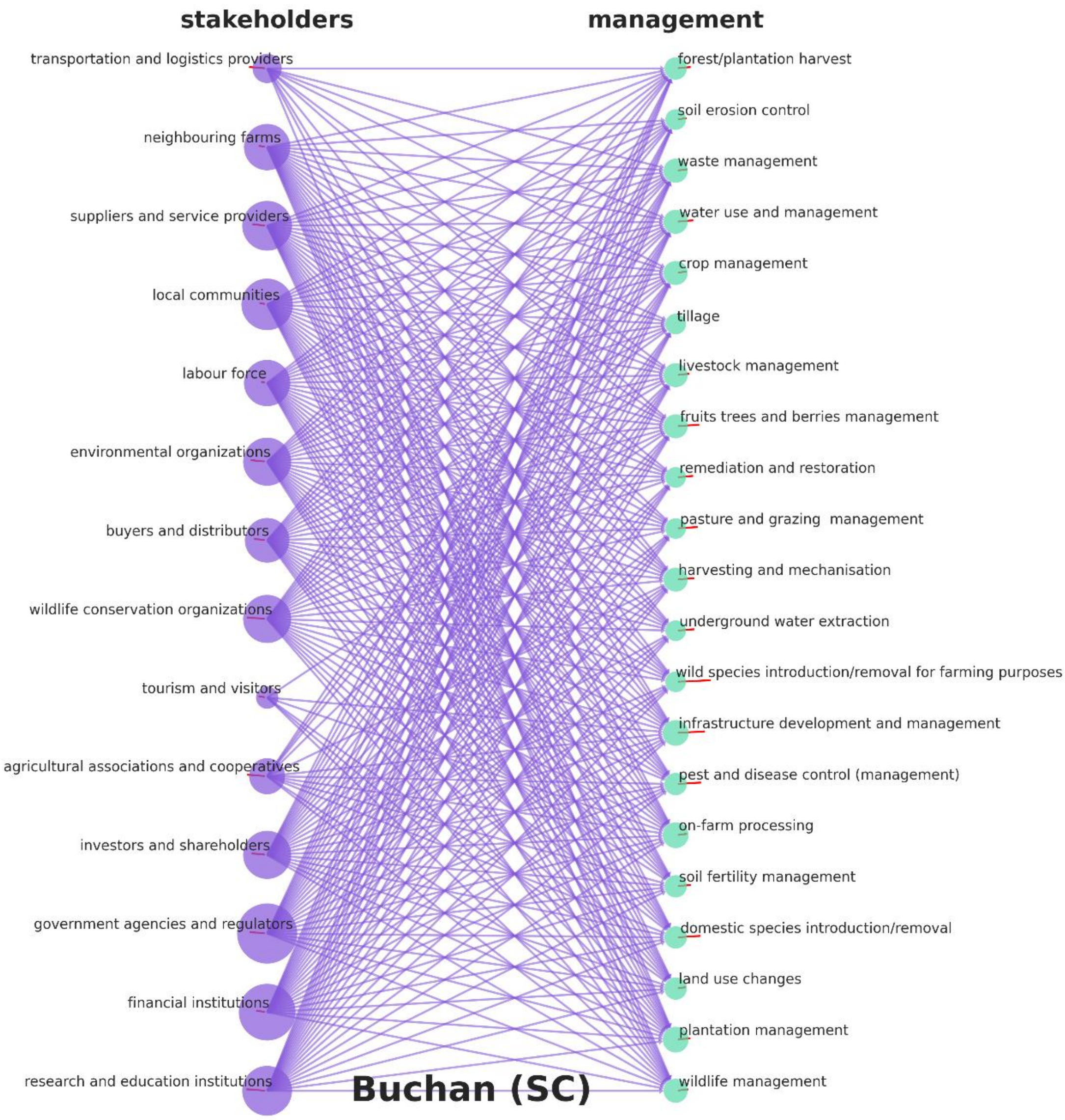

Figure 8. Directed interactions from the stakeholder to the management layer in Buchan. Node size in the stakeholder layer is proportional to their out-degree centrality, while in the management layer it is proportional to the in-degree centrality.

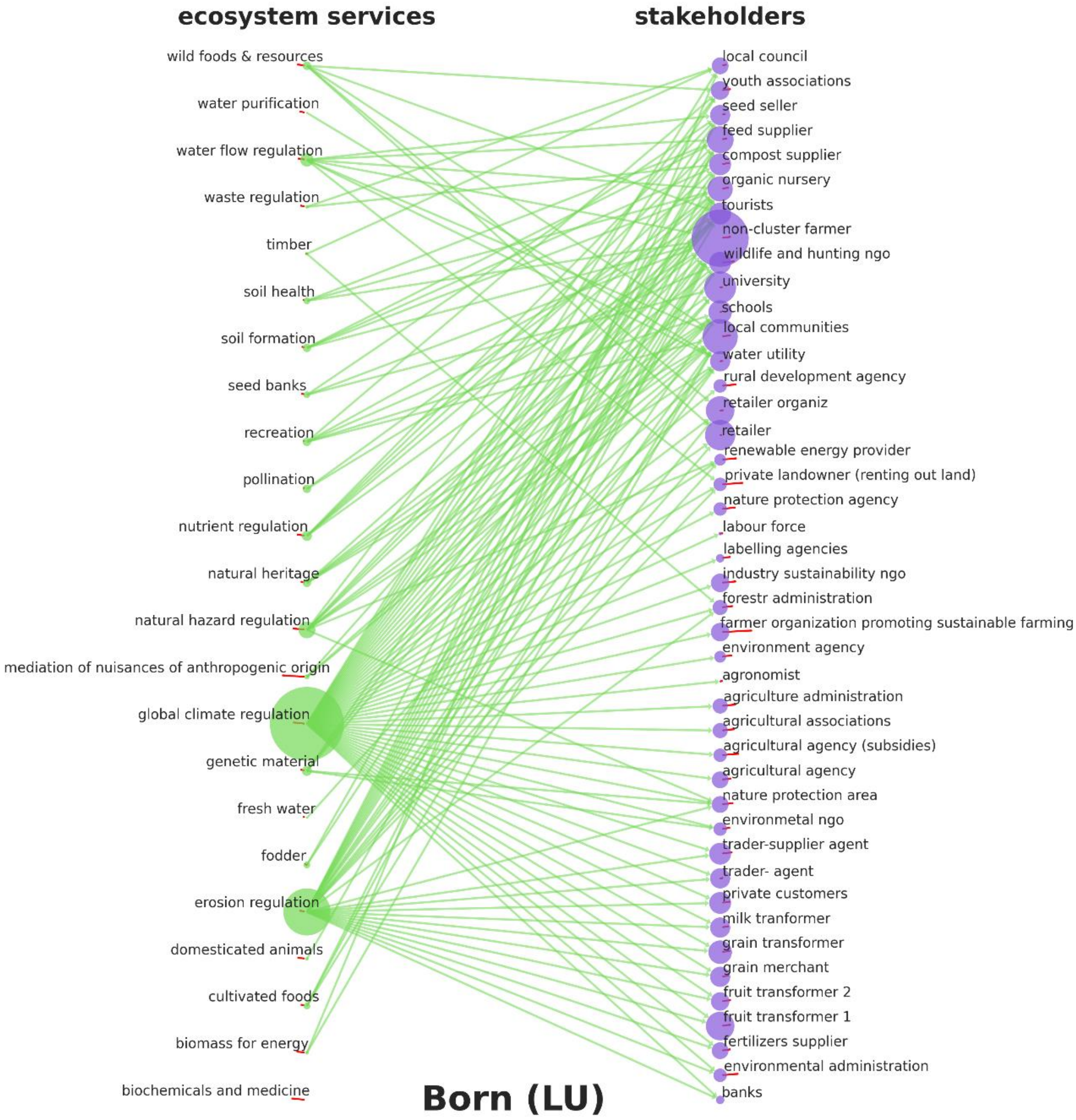

Figure 9. Directed interactions from the ecosystem services to the stakeholder layer in Born. Node size in the ecosystem services layer is proportional to their out-degree centrality, while in the stakeholder layer it is proportional to the in-degree centrality.

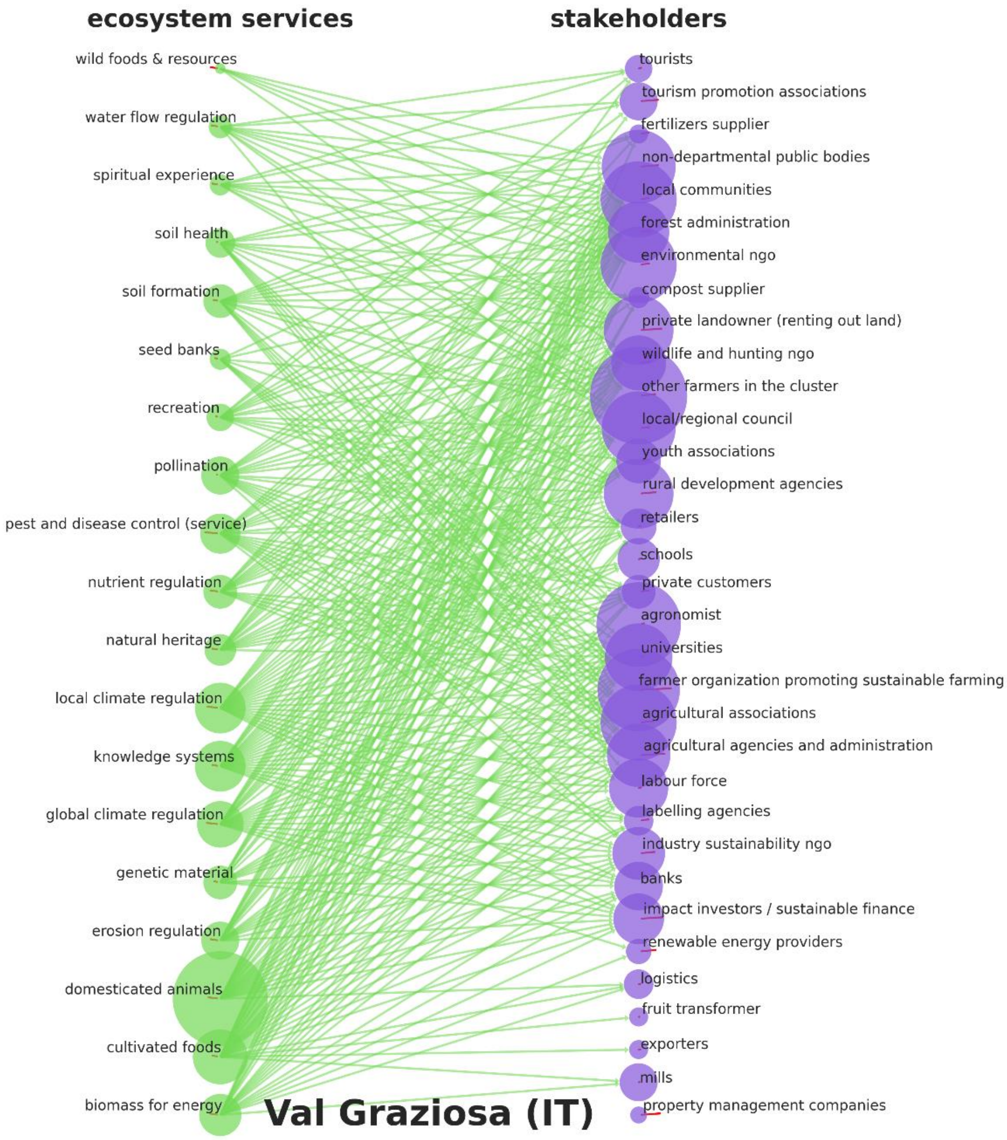

Figure 10. Directed interactions from the ecosystem services to the stakeholder layer in Val Graziosa. Node size in the ecosystem services layer is proportional to their out-degree centrality, while in the stakeholder layer it is proportional to the in-degree centrality.

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6.2.1 Topological properties of the networks

In this part, we adopted a systemic scope, and we focused on understanding networks characteristics beyond the visual aspects that stand out. More specifically, in this section we analysed some general systems' properties by describing their topology, and by contrasting the empirically built networks with other theoretical and well-studied network models such as the scale-free or random networks (Gómez-Gardeñes, J., & Moreno, 2006). This exercise served as a theorical validation of the consistency and plausibility of the networks built from the identification of nodes and edges in the data collection stage.

Since we are dealing with directed networks, we started plotting the in (i.e. Figure 11a) and out (i.e. Figure 11) -degree distributions separately using a log-log scale. The systems have an average in (<k_in>) and out (<k_out>) degree of 7.8, 14.25, and 13.94 for Born, Val Graziosa, and Buchan systems, respectively. This means that the degree (i.e. in and out combined) of a node is, on average, 14.25, 28.5, and 27.88 for each one of the three systems, respectively. From this and the degree distributions in Figure 11, it is possible to say that Val Gracioza and Buchan are topologically more similar to each other than to Born.

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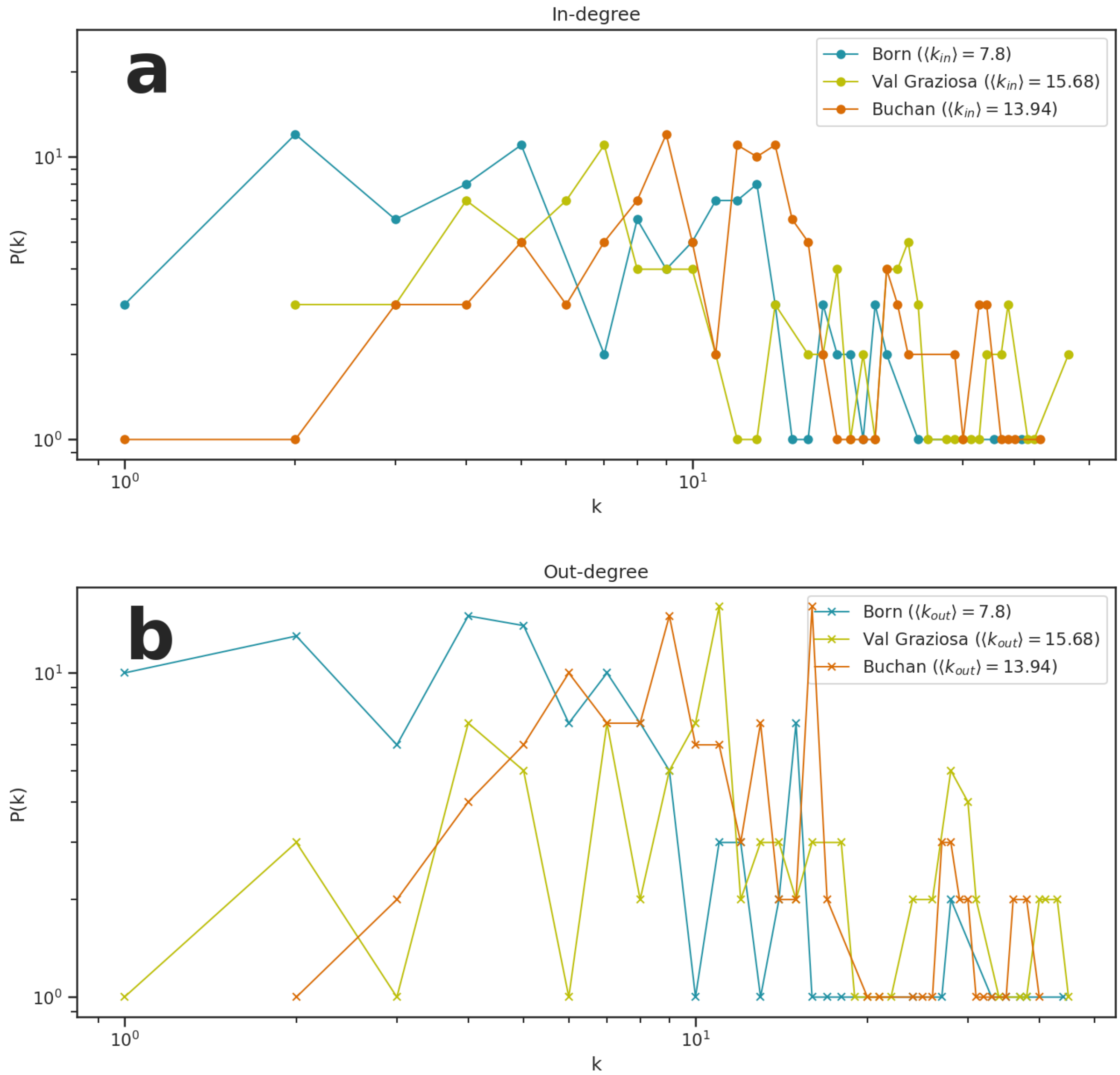

Figure 11. In (a) and out (b) -degree distributions. Colours indicate the study system. <k_in> and <k_out> indicate the average in or out–degree, respectively.

From the in and out -degree distributions (Figure 12), it can be noted that a common characteristic among the three systems is the presence of long tails and highly connected nodes. For instance, in the Born system (Figure 12b) the probability of finding nodes with an out-degree lower than the average -i.e., 7.8- is higher than the probability of finding nodes with an out-degree greater than 7.8. In this case, these nodes can be up to five times more connected than the average node. This means that, in the three systems, highly connected nodes are scarce while the poorly connected ones are abundant. In the literature, these scare but highly connected nodes are called hubs, and their presence is a characteristic of networks with scale-free properties. These properties are important because they can be found in real world networks like supply chains (Gao et al., 2016). Since our aim is to address the consistency of the empirical network, we focussed on evaluating how similar are the three systems to a theoretical scale-free network (Barabasi and Albert, 1999) and to a randomly generated network

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(Erdos and Renyi, 1959). On the one hand, in scale-free networks, the degree distribution has a long tail, nodes with few connections are abundant, and few nodes are considerably more connected than the average (i.e., hubs). On the other hand, in a randomly generated network, the degree distribution has a short tail, and it is distributed around the average degree (Annex xii). As mentioned before, Figure 12 shows that the three systems contain hubs that have degrees much higher than the network's average (i.e., long tail), meaning that the systems do not have random network properties.

While there is no formal method to determine if a network is scale-free, we can say that a network has scale-free properties when the degree distribution follows a power law and when there is a tail of high degree nodes (Albert-Laszlo Barabasi, 2013). In this sense, the following step consisted in determining how similar are the systems' degree distribution to a power law. For this, we fitted the degrees to a power law distribution parametrised by alpha (Alstott et al., 2014) and we compared the parameter alpha of the best fit to the different alpha values observed in other scale-free networks from the literature.

As it can be shown in Annex (xi) all systems have alpha values between 2.13 and 2.59. As it has been exhaustively discussed by Barabasi and Albert (1999), scale-free networks commonly have an alpha parameter that ranges between 2 and 3. In this manner, in addition to the presence of hubs, we can suggest that these networks exhibit some scale-free property, and they are far from having a random topology.

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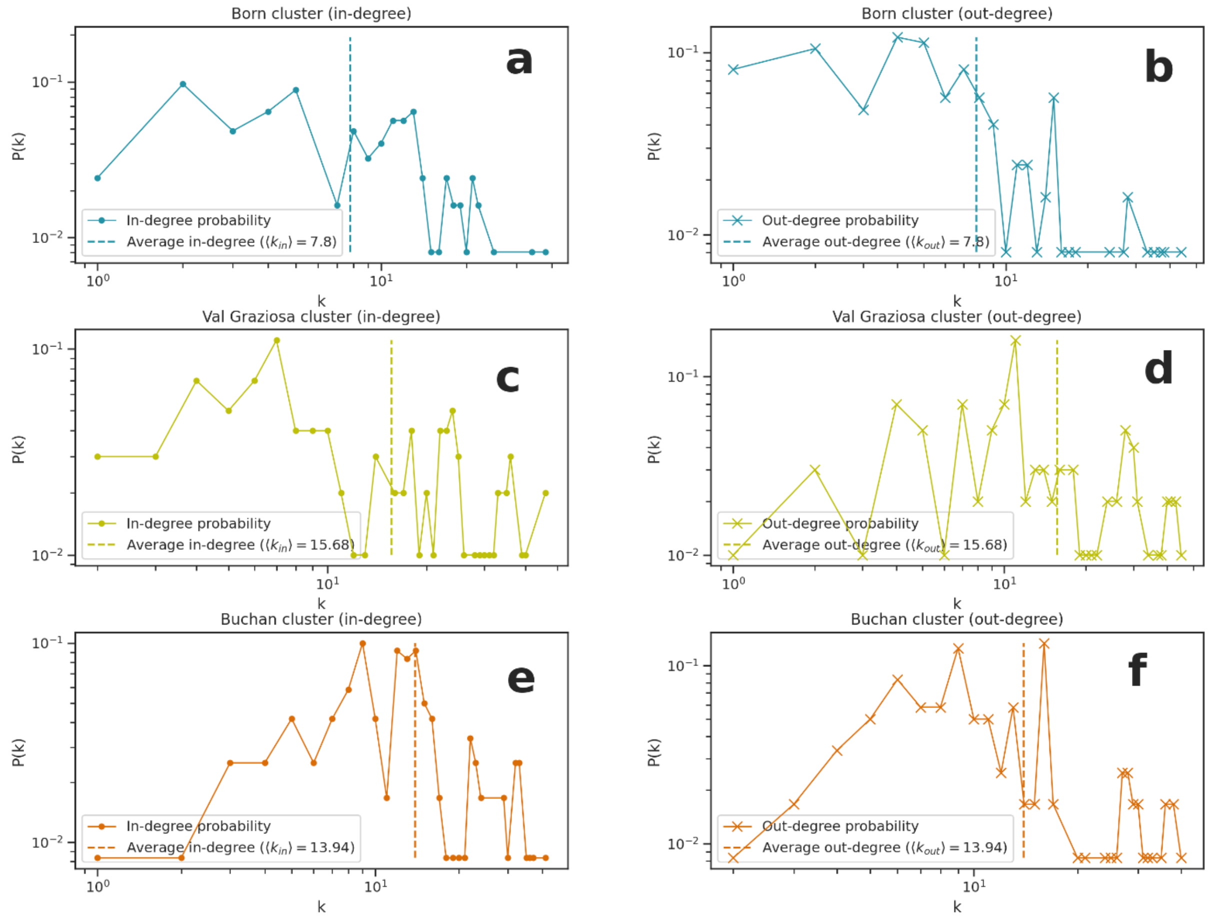

Figure 12. In and out –degree distributions for the Born (a and b, respectively), Val Graziosa (c and d, respectively). and Buchan (e and f, respectively) systems. The continuous line indicates the probability distribution, and the dashed line shows the average in and out –degree.

6.3. Hubs identification and centrality analysis

We relied on the different centrality metrics described in section 7 to rank the nodes. As it is shown in Figure 13 to Figure 15, nodes ascend in the ranking in the right-hand side, and they are highlighted with the colour of their corresponding layer. Depending on the type of metric, nodes may have a different ranking, for which we used the coloured connected lines to help identifying them.

6.3.1 Degree, in and out-degree centrality analyses

Firstly, we ranked them using local centralities, such as degree, in and out-degree centralities (see Figure 13 to Figure 15).

In Buchan ecological entities are primarily located in the upper quartile, especially in degree and in-degree centrality, while ecological processes are evenly spread across all quartiles. Ecosystem services and management in this cluster are mostly found in the lower and median quartiles, with stressors distributed across the top-median, bottom-median, and upper quartiles, but absent in the lower quartile. Stakeholders are concentrated in the upper quartile. Val Garziosa, on the other hand, sees ecological entities concentrated in the upper quartile, with a significant presence in the top-median

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quartile, particularly in in-degree and out-degree centrality. Ecological processes and stressors are predominantly in the lower quartile, with some distribution in the bottom-median quartile. Ecosystem services and management are more evenly spread, with management concentrated in the top-median quartile but placed in the lower quartile when considering out-degree centrality. Stakeholders are primarily found in the upper quartile but also have significant representation in the top-median and lower quartiles. Born on the other hand shows more variability. Ecological entities are primarily in the upper quartile but are also spread across the top-median, bottom-median, and lower quartiles in out-degree centrality. Ecological processes and stressors are concentrated in the lower quartile, particularly in degree and out-degree centrality, with some presence in the bottom-median quartile. Ecosystem services and management are predominantly in the lower quartile, but with broader distribution across other quartiles.

Stakeholders Born cluster exhibit a more even distribution across all quartiles, with notable concentrations in both the upper and lower quartiles. Overall, while Buchan and Val Graziosa often position entities and stakeholders in the upper quartile, the Born demonstrates greater variability and a more even spread across different centrality measures, particularly for processes, services, and stressors.

Table 2 shows the most influential ecological entities in terms of impacting the provision of ecosystem services and processes (out degree centrality). In Buchan, the most influential ecological entities are crops, fruit trees and berry plantations, weeds/forbs, grasses and natural forest. In Val Graziosa, the most influential ecological entities are fruit trees and berry plantations, grasses, herbivores birds, herbivores insects, and natural forest. In Born, the most influential ecological entities are crops, domestic grazers, natural forest, plantations, predatory birds, and predatory insects.

Table 3 shows the most influential stakeholders in terms of impacting management practices (out degree centrality). In Buchan, the most influential stakeholders are government agencies and regulators, financial institutions, local communities, research and education institutes, suppliers and service providers. In Val Garziosa, the most influential stakeholders are local/regional council, rural development agencies, logistics companies, non-departmental public bodies, and banks. In Born, the most influential stakeholders are water utility companies, labour force, renewable energy providers, banks, and nature protection agencies.

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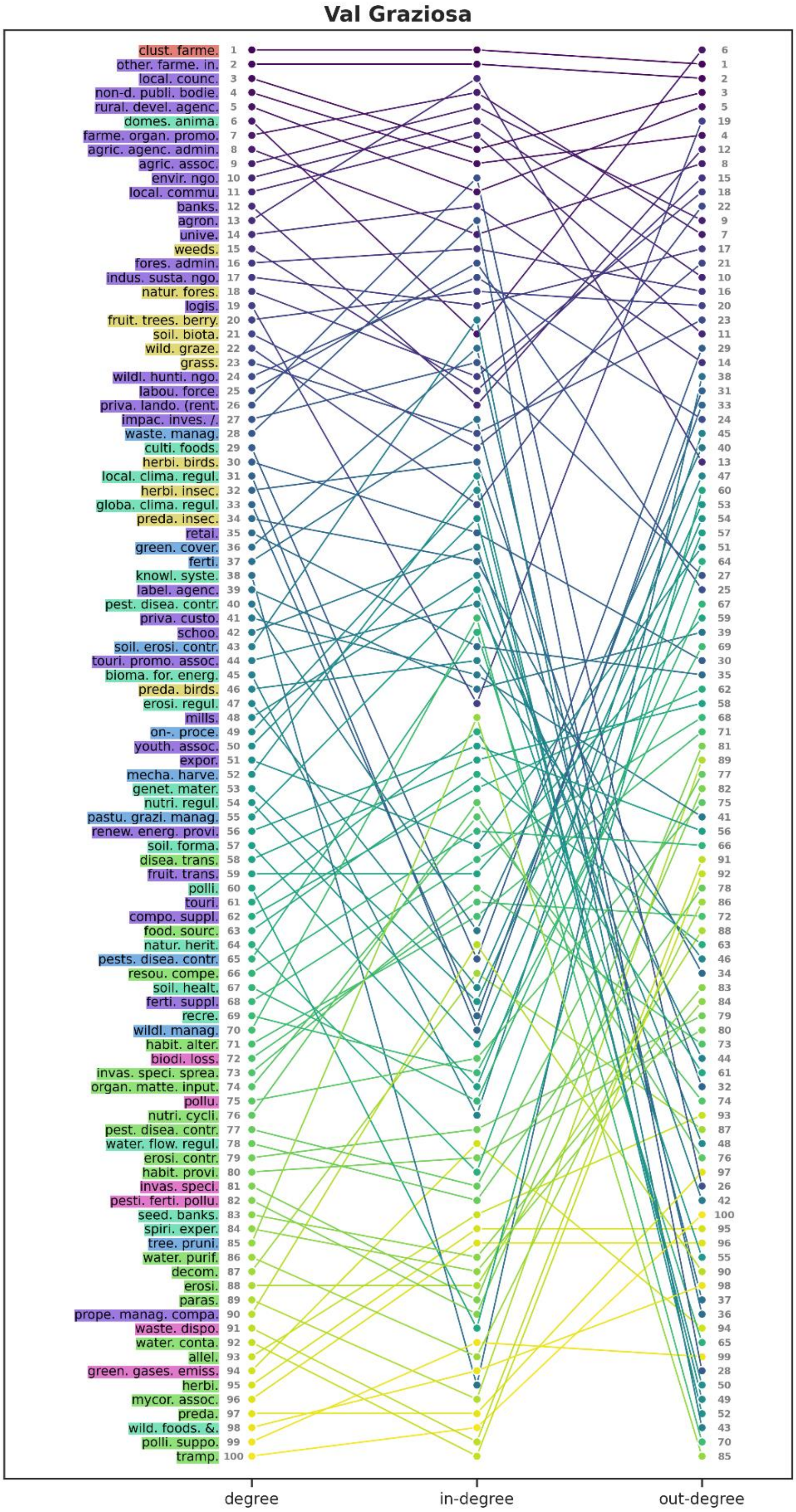

Figure 13. Nodes ranking based on degree, in-degree, and out-degree centrality for the Val Graziosa (Italy) system. Nodes' background colour indicates the corresponding layer.

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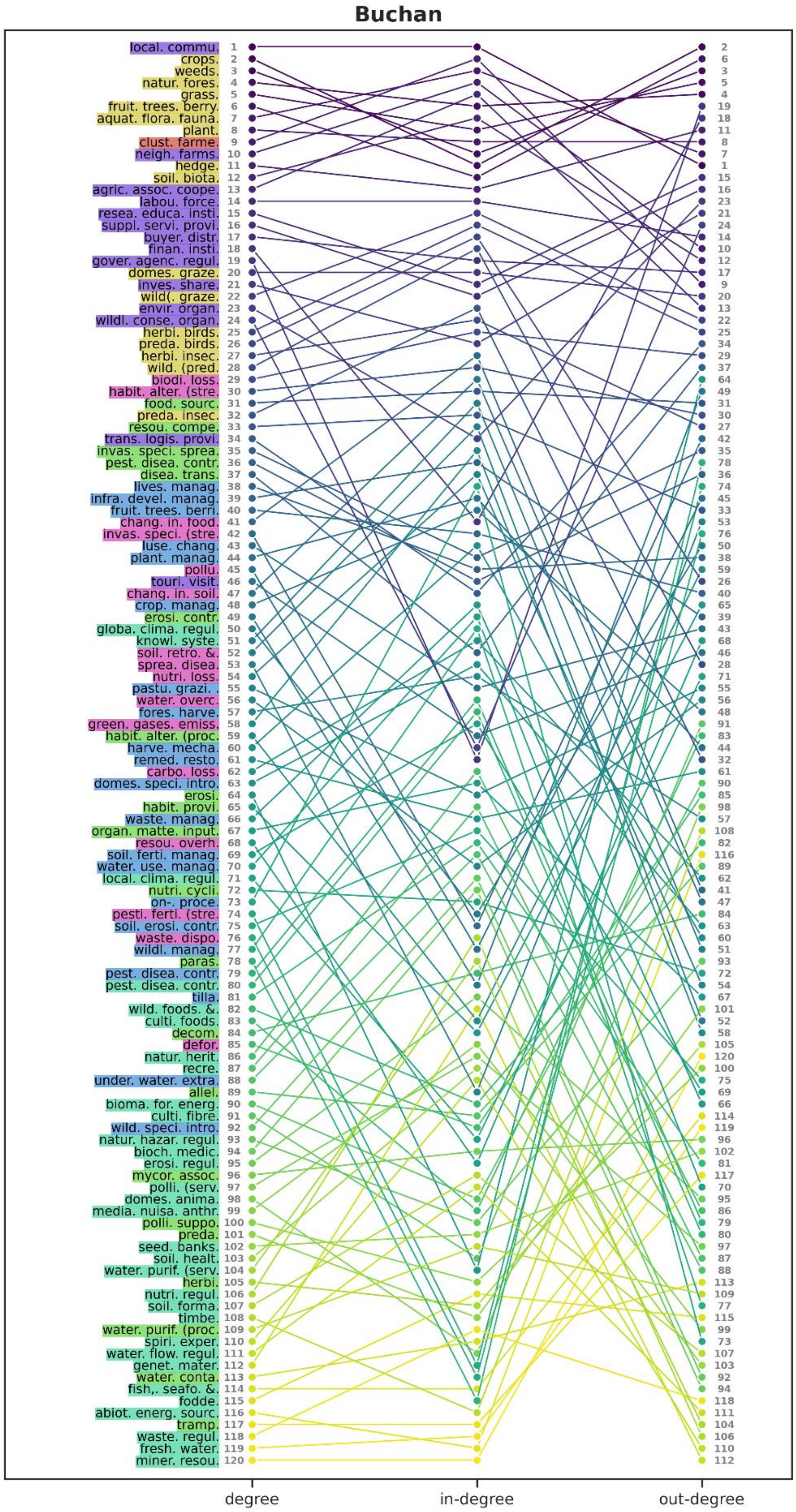

Figure 14. Nodes ranking based on degree, in-degree, and out-degree centrality for the Buchan (Scotland) system. Nodes' background colour indicates the corresponding layer.

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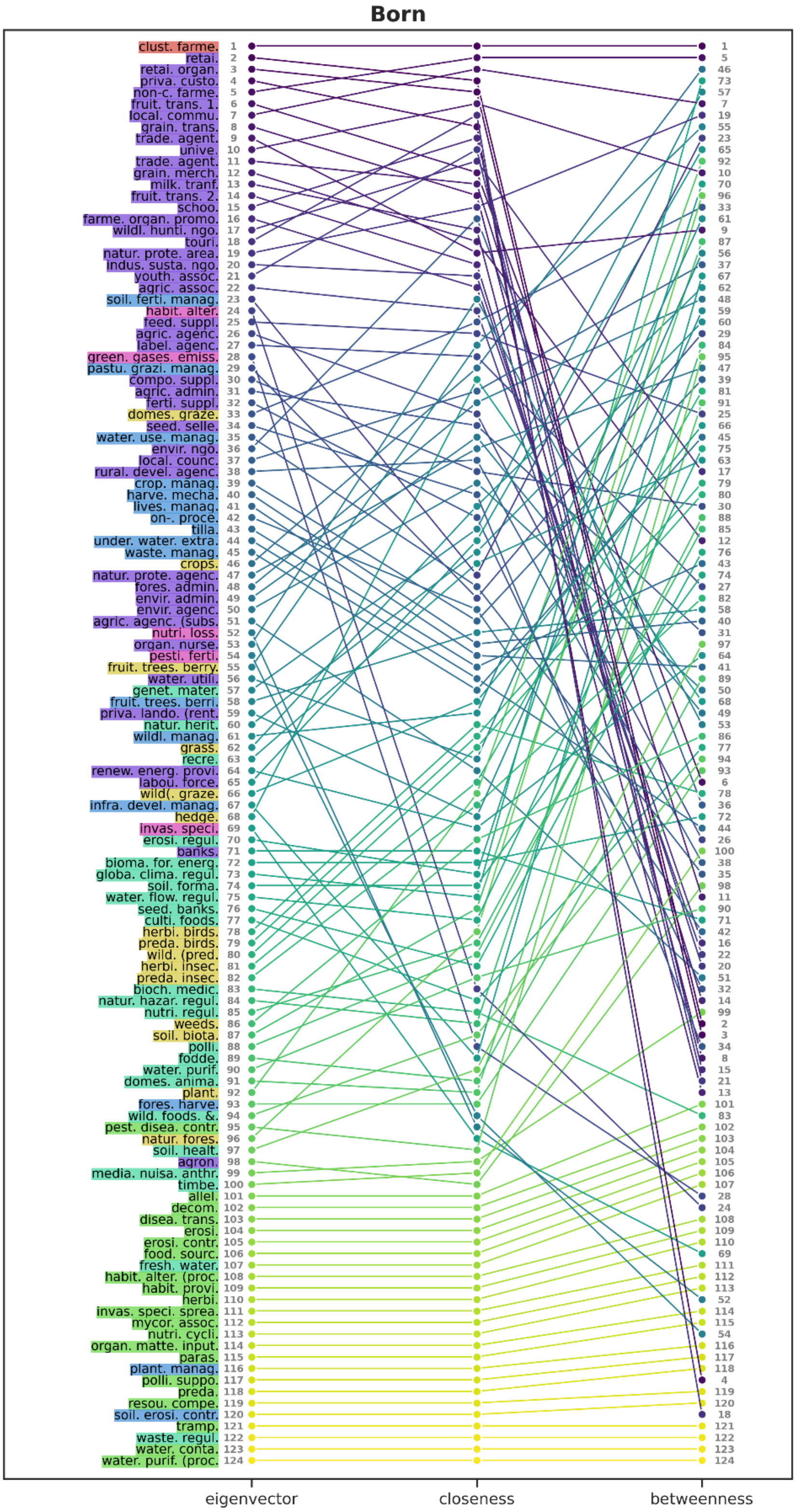

Figure 15. Nodes ranking based on degree, in-degree, and out-degree centrality for the Born (Luxembourg) system. Nodes' background colour indicates the corresponding layer.

Table 2. The most influential ecological entities in terms of impacting the provision of ecosystem services and processes for the three clusters.

	Buchan		Val Graziosa		Born	
	Out degree value	Rank	Out degree value	Rank	Out degree value	Rank
aquatic flora and fauna	0.252	8	na	na	na	na
crops	0.336	1	na	na	0.114	1
domestic grazers	0.202	10	na	na	0.016	2
fruit trees and berry plantations	0.319	2	0.312	1	0.098	12
grasses	0.303	4	0.284	2	0.041	14
hedgerows	0.269	6	na	na	0.024	9
herbivores birds	0.143	12	0.284	3	0.016	11
herbivores insects	0.134	13	0.275	4	0.041	15
natural forest	0.303	5	0.257	5	0.138	3
plantations	0.261	7	na	na	0.114	4
predatory birds	0.118	14	0.257	6	0.033	5
predatory insects	0.092	16	0.11	7	0.033	6
soil biota	0.227	9	0.092	8	0.089	13
weeds/forbs	0.319	3	0.092	9	0.024	10
wild (predators)	0.109	15	na	na	0.033	7
wild(grazers)	0.168	11	0.073	10	0.033	8

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Table 3. The most influential stakeholders in terms of impacting management practices.

	Buchan		Val Graziosa		Born	
	Out degree	rank	Out degree	rank	Out degree	rank
agricultural agencies and administration	na	na	0.339	7	0.073	25
agricultural agency (subsidies)	na	na	na	na	0.073	26
agricultural associations	0.176	12	0.275	10	0.033	9
agronomist	na	na	0.165	16	0.049	32
banks	na	na	0.349	6	0.220	5
buyers and distributors	0.218	11	na	na	na	na
compost supplier	na	na	0.101	26	0.024	14
environment agency	na	na	na	na	0.146	7
environmental administration	na	na	na	na	0.057	28
environmental ngo	0.235	6	0.257	13	0.057	29
exporters	na	na	0.138	17	na	na
farmer organization promoting sustainable farming	na	na	0.275	9	0.033	10
feed supplier	na	na	na	na	0.033	11
fertilizers supplier	na	na	0.101	25	0.033	12
financial institutions	0.277	2	na	na	na	na
forest administration	na	na	0.257	12	0.049	33
fruit transformer	na	na	0.119	21	0.033	13
government agencies and regulators	0.294	1	na	na	na	na
grain merchant	na	na	na	na	0.024	15
grain transformer	na	na	na	na	0.016	16
impact investors / sustainable finance	na	na	0.128	19	na	na
industry sustainability ngo	na	na	0.275	8	0.041	36
investors and shareholders	0.235	7	na	na	na	na
labelling agencies	na	na	0.119	20	0.131	8
labour force	0.227	9	0.128	18	0.301	2
local communities	0.252	3	0.257	11	0.073	22
local council	na	na	0.376	3	0.065	27
milk tranformer	na	na	na	na	0.016	17
mills	na	na	0.064	31	na	na
nature protection agency	na	na	na	na	0.195	6
neighbouring farms	0.227	10	0.394	1	0.228	4
non-departmental public bodies	na	na	0.367	4	na	na
private customers	na	na	0.101	24	0.000	42
private landowner (renting out land)	na	na	0.064	30	0.057	30
property management companies	na	na	0.046	32	na	na
renewable energy provider	na	na	0.101	23	0.285	3
research and education institutions	0.244	4	0.239	14	0.073	24
retailers	na	na	0.110	22	0.008	38
rural development agencies	na	na	0.376	2	0.073	23
schools	na	na	0.064	29	0.008	40
seed seller	na	na	na	na	0.016	19
suppliers and service providers	0.244	5	na	na	0.089	21
tourism and visitors	0.109	14	0.083	27	0.000	43
tourism promotion associations	na	na	0.083	28	na	na
transportation and logistics providers	0.143	13	na	na	na	na
water utility	na	na	na	na	0.309	1
wildlife conservation organizations	0.235	8	0.193	15	0.057	31
youth associations	na	na	0.037	33	0.008	41

6.3.2 Eigenvector, closeness and betweenness centrality analyses

Secondly, we ranked using metrics that consider topological properties, such as eigenvector centrality, closeness and betweenness (see Figure 16 to Figure 18). Ecological entities in Buchan consistently occupy the upper quartile across all centrality measures, underscoring their prominent role within the network. In Val Graziosa, ecological entities are generally distributed between the upper and top-median quartiles for betweenness and closeness centrality. However, they are concentrated in the bottom-median quartile when assessed by eigenvector centrality, indicating a potential decrease in influence. Born presents a more even distribution of ecological entities across quartiles, with notable representation in the bottom-median and top-median quartiles and some presence in the upper quartile for betweenness and closeness centrality. Buchan’s ecological entities demonstrate consistently high centrality, highlighting their considerable influence in the network. Val Graziosa, while also showing high centrality in betweenness and closeness, reveals a shift toward lower centrality in eigenvector measures, suggesting a more nuanced role. Born’s distribution suggests a more diversified or less centralised role of ecological entities, with no clear dominance in any quartile.

Ecological processes in Buchan are predominantly found in the lower quartiles, particularly in betweenness and eigenvector centrality, but they are scattered in the ranking when observing closeness centrality. Val Graziosa shows a similar pattern, with ecological processes primarily concentrated in the lower quartile across all centrality measures, with some presence in the bottom-median quartile. Born mirrors Val Graziosa, with ecological processes almost entirely located in the lower quartile. Both Val Graziosa and Born exhibit a strong concentration of ecological processes in the lower quartile across all centrality measures, indicating their reduced influence or importance within the network. Buchan, while also showing a lower quartile concentration, has a slightly broader distribution, suggesting a more integrated, though still limited, role for ecological processes.

Ecosystem services in Buchan are mainly distributed across the lower and bottom-median quartiles, with minimal presence in the upper quartile. Val Graziosa shows a similar pattern, with ecosystem services primarily located in the lower and bottom-median quartiles, though with minor representation in the top-median and upper quartiles. In Born, ecosystem services are concentrated in the bottom-median quartile, with a small presence in the lower quartile. Ecosystem services across all three regions are predominantly found in the lower and bottom-median quartiles, reflecting a lower centrality within the network. However, Buchan and Val Graziosa show slightly more presence in the upper quartiles, indicating a higher recognition of their importance in certain contexts compared to Born.

Management activities in Buchan are largely distributed within the top-median quartile, with additional presence in the bottom-median quartile. Val Graziosa demonstrates a high centrality for management, particularly in betweenness and eigenvector centrality, where it is concentrated in the upper quartile, while closeness centrality places it entirely in the top-median quartile. In Born, management is primarily situated in the top-median quartile but exhibits a more even spread across other quartiles, especially in eigenvector centrality. Val Graziosa’s management is strongly centralised in the upper quartile, particularly in betweenness and eigenvector centrality, signifying its pivotal role within the network. In contrast, Buchan and Born exhibit a more balanced distribution, with management spread across the top-median and bottom-median quartiles, suggesting a significant but less dominant role.

Stakeholders in Buchan are mainly positioned in the upper quartile, with some distribution in the top-median quartile. Val Graziosa similarly positions stakeholders predominantly in the upper quartile, with additional presence in the top-median quartile, though eigenvector centrality shows an even split between these two quartiles. In Born, stakeholders are more evenly distributed across quartiles, with significant concentrations in the upper and top-median quartiles. Stakeholders in Buchan and Val Graziosa are strongly centralised in the upper quartile, highlighting their crucial importance within the network. Born, however, presents a broader distribution, indicating a more diversified role for stakeholders and a less centralised network structure.

Stressors in Buchan are confined to the lower quartile in closeness centrality but are more widely distributed across the upper and median quartiles in betweenness and eigenvector centrality. In Val Graziosa, stressors are entirely within the bottom-median quartile for closeness centrality, but with a notable concentration in the upper quartile for betweenness centrality and in the top-median quartile for eigenvector centrality. Born consistently places stressors in the lower quartile across all measures, with limited presence in the bottom-median quartile.

Overall, Buchan emphasises strong centrality for ecological entities and stakeholders, while management and ecosystem services play significant but less centralised roles. Stressors and ecological processes generally exhibit lower influence, except in specific centrality measures. Val Graziosa follows a similar pattern, with strong centrality for stakeholders and ecological entities, particularly in betweenness centrality. Management is highly central, while stressors and ecosystem services exhibit varying levels of influence depending on the measure, reflecting a complex, context-dependent network role. Born, with its more even distribution across all components, highlights a less hierarchical and more interconnected network structure, where ecological processes and stressors consistently rank lower, and ecological entities, management, and stakeholders show more variability.

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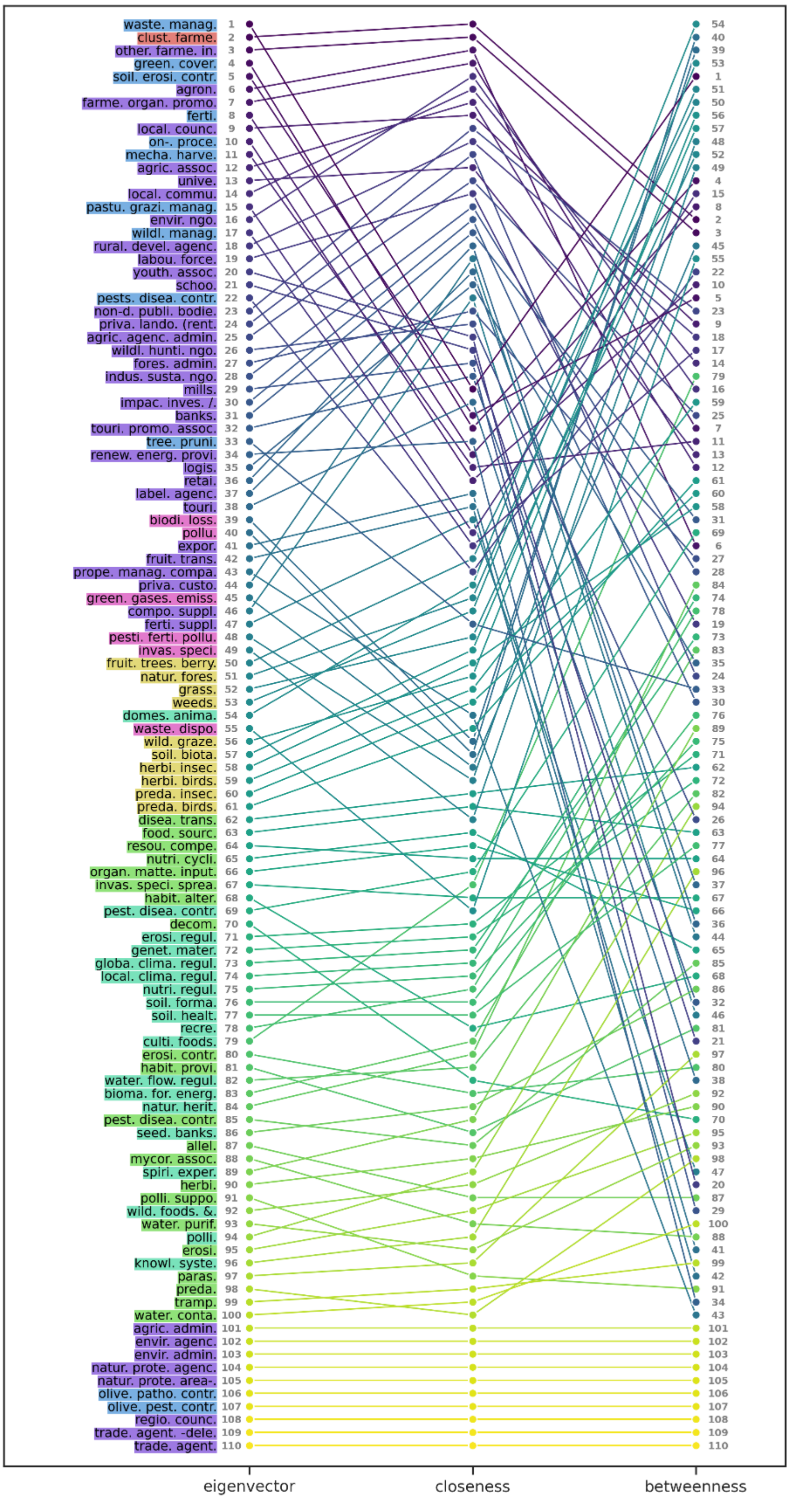

Figure 16. Nodes ranking based on degree, in-degree, and out-degree centrality for the Val Graziosa (Italy)system. Nodes' background colour indicates the corresponding layer.

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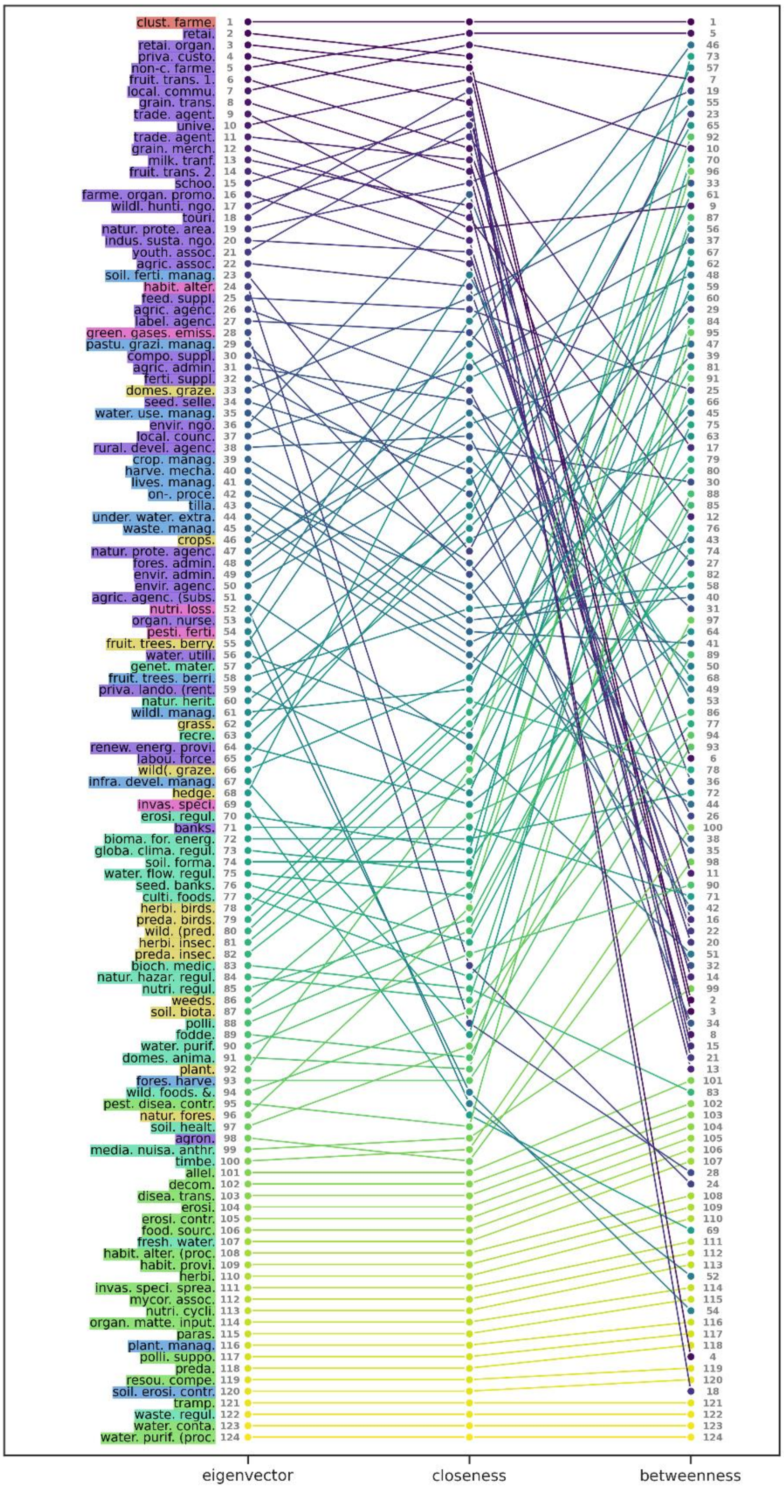

Figure 17. Nodes ranking based on degree, in-degree, and out-degree centrality for the Born (Luxembourg) system. Nodes' background colour indicates the corresponding layer.

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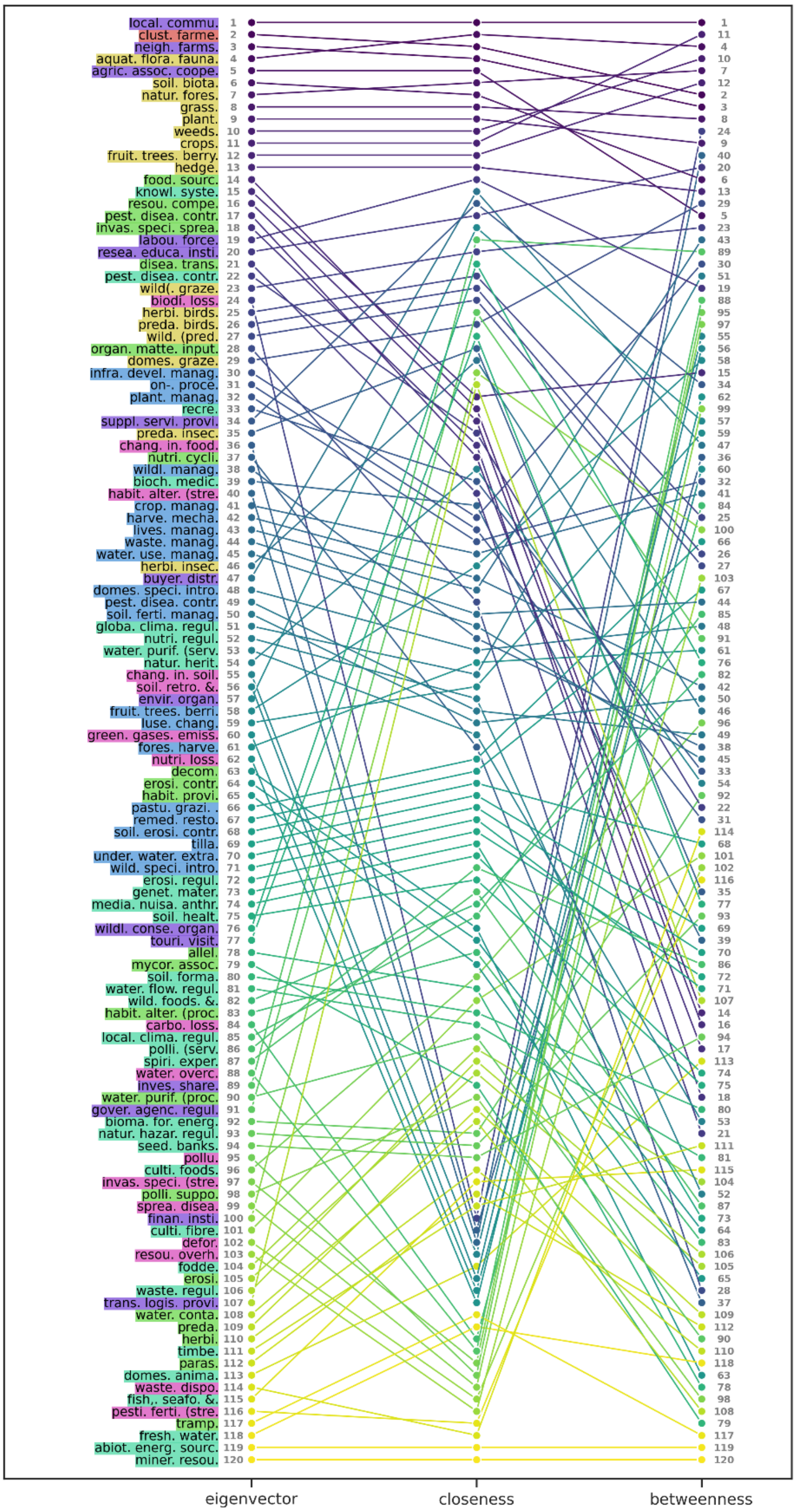

Figure 18. Nodes ranking based on degree, in-degree, and out-degree centrality for the Buchan (Scotland) system. Nodes' background colour indicates the corresponding layer.

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6.4. Interlayer distance.

We calculated the average distance (i.e. shortest path length) between any node of a layer to any other node from the rest of the layers. In other words, the average distance is the average minimum 'steps' required to go from one layer to another. This average interlayer distance serves a proxy of complexity since we assume that every step (i.e. edge) implies the operation of an additional dynamic process. In this sense, the more steps required to go from node (i.e. or layer) to another, the more complex is the dependency between these two nodes. In a similar fashion, less steps mean that the dependency among nodes is less complex. In Figure 19 to Figure 21, we represented this interlayer average distance in graphs where the nodes are layers, and the directed edges (arrows) label indicate the average distance from a layer to another. To facilitate the interpretation, arrows width sizes are set proportional to average distance and the colour is set to match the origin layer.

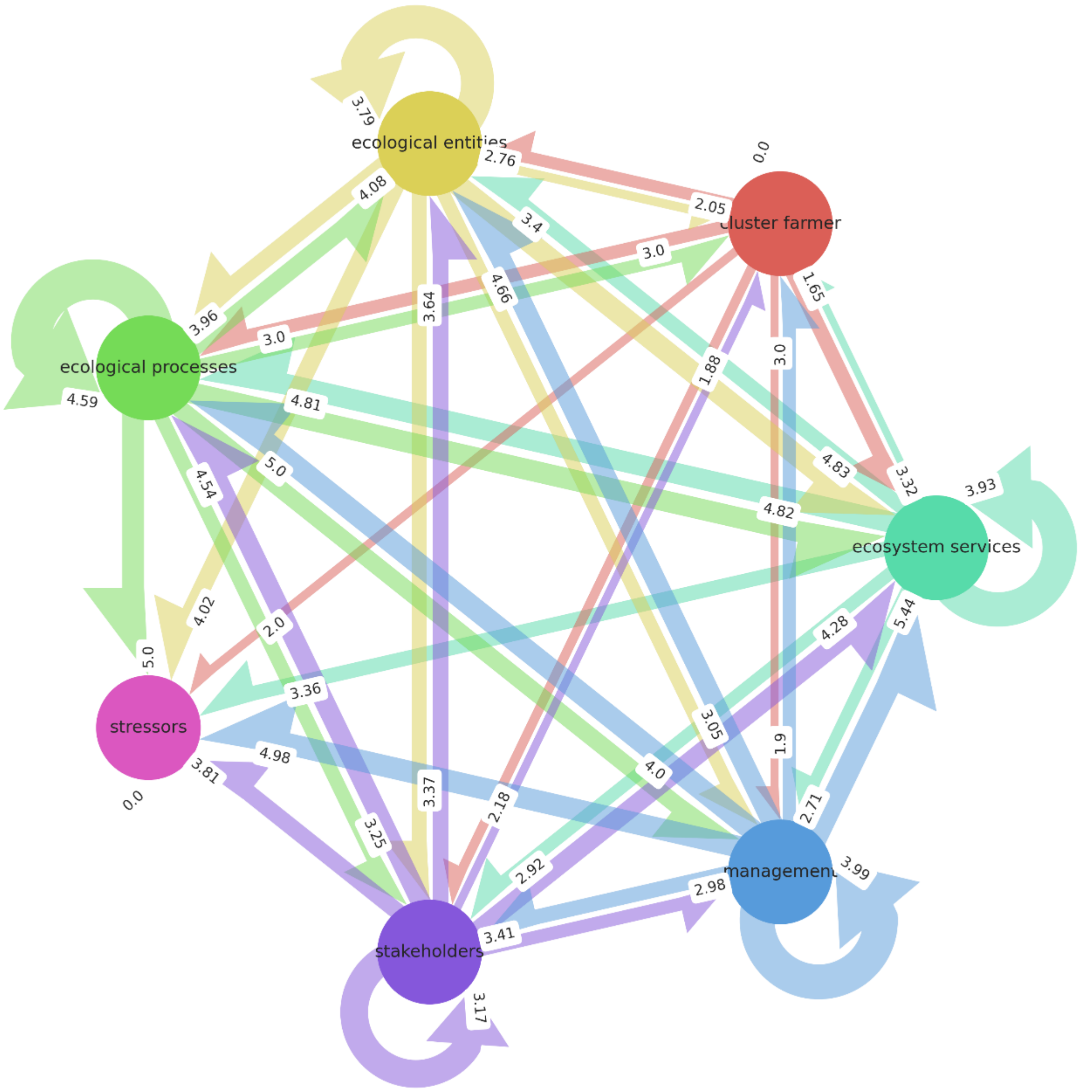

Figure 19. Average distance that connects two layers in Born. It is obtained from averaging the shortest path length of all nodes from one layer to all the nodes from the rest of the layers. Arrow width size is proportional to average distance. Arrow colour indicates the origin layer.

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Figure 20. Average distance that connects two layers in the Buchan cluster. It is obtained from averaging the shortest path length of all nodes from one layer to all the nodes from the rest of the layers. Arrow width size is proportional to average distance. Arrow colour indicates the origin layer.

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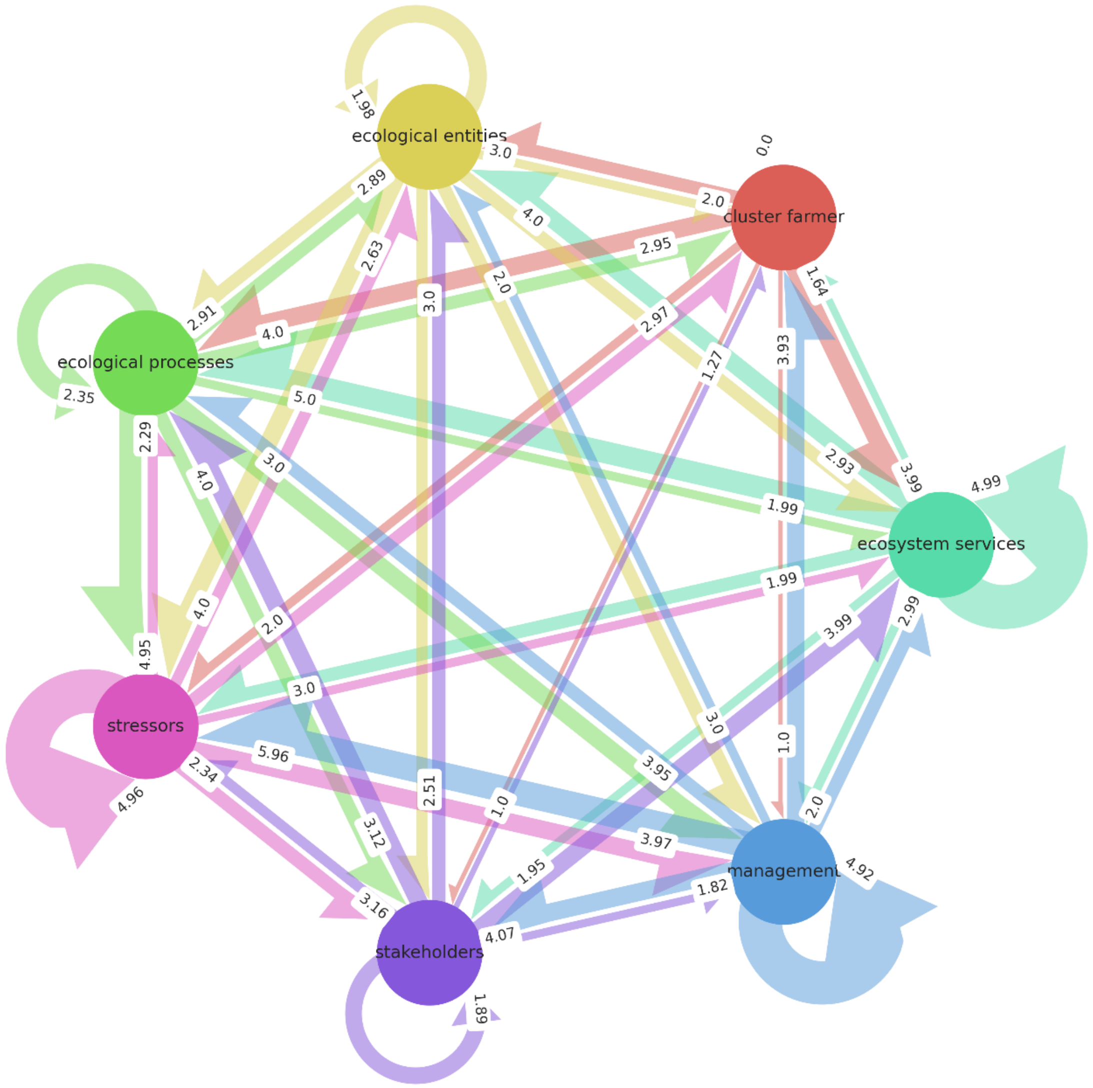

Figure 21. Average distance that connects two layers in the Val Graziosa cluster. It is obtained from averaging the shortest path length of all nodes from one layer to all the nodes from the rest of the layers. Arrow size is proportional to average distance. Arrow colour indicates the origin layer.

6.5. Cycles and relevant interactions

In order to understand the potential presence of feedback loops, we searched for possible cycles in the three systems. In a directed graph, a cycle is a path containing a non-null sequence of non-repeating edges where only the first and last nodes are the same. The rationale behind this exercise was to identify some complex dynamics and to distinguish which ones are relevant or easier to address in the context of the project's objectives. Relying on a graph traversal algorithm, we considered a maximum length of five steps to identify the loops. This threshold was set given that the computational cost increased exponentially when higher thresholds were considered (see Annex ii). As it can be seen in Figure 22, the Italian and the Scottish cluster present higher number of cycles regardless of the threshold except when the threshold is three. In fact, given that logarithm scale of the vertical axis, it can be noted that the Luxembourgish cluster contains considerably less cycles than the rest of clusters.

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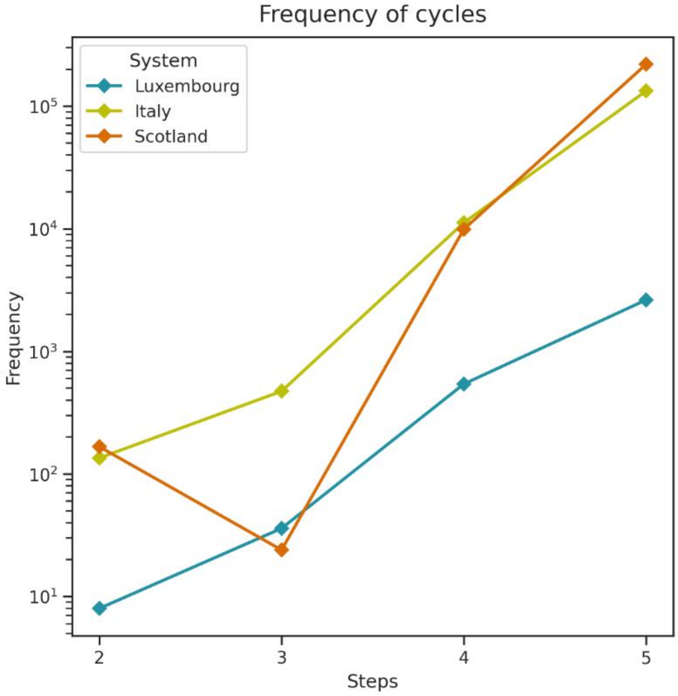

Figure 22. Frequency of cycles for the three systems. The x axis refers to the maximum length of the cycle ingested as a threshold to the graph traversal algorithm.

To understand the potential importance of these cycles we sought to describe them but due to the number of cycles in the networks, it was impractical to identify and describe all of them. To overcome this, we focussed cycles that contained the nodes in layers of interest, 'cluster farmer' and 'ecological entities', selecting only the cycles that included at least one node of each of these layers. We prioritised the cluster of farmers since this node is under constant observation and most of the potential interventions will be targeting these agents, Similarly, we focussed on ecological entities since they represent endpoints of interest in the context of the FRAMEWORK project (i.e., biodiversity conservation).

For each cycle, we summed the nodes' eigenvector centrality, and we ranked the cycles prioritising the ones with higher aggregation. As it can be seen in Figure 23, the four highest scoring cycles in the Scottish cluster represent simple cycles. In fact, in all the cases, there are four nodes in common (i.e. biodiversity loss, aquatic flora and fauna, knowledge systems, and cluster farmers), while the nodes that vary between cycles are members of the 'management' layer. In the case of the Italian system (Figure 24), we observe a similar pattern in which variation in an 'ecological entities' node gives rise to several forms of an otherwise common cycle Finaly, when observing the Luxembourgish cluster, we see that only the university, cluster farmer, and genetic material nodes repeat, while the rest of nodes belong to distinct layers. Moreover, differently from the previous cases, in this system we see the presence of bidirectional interactions, meaning that these cycles contain other smaller cycles (i.e. university <-> cluster farmer).

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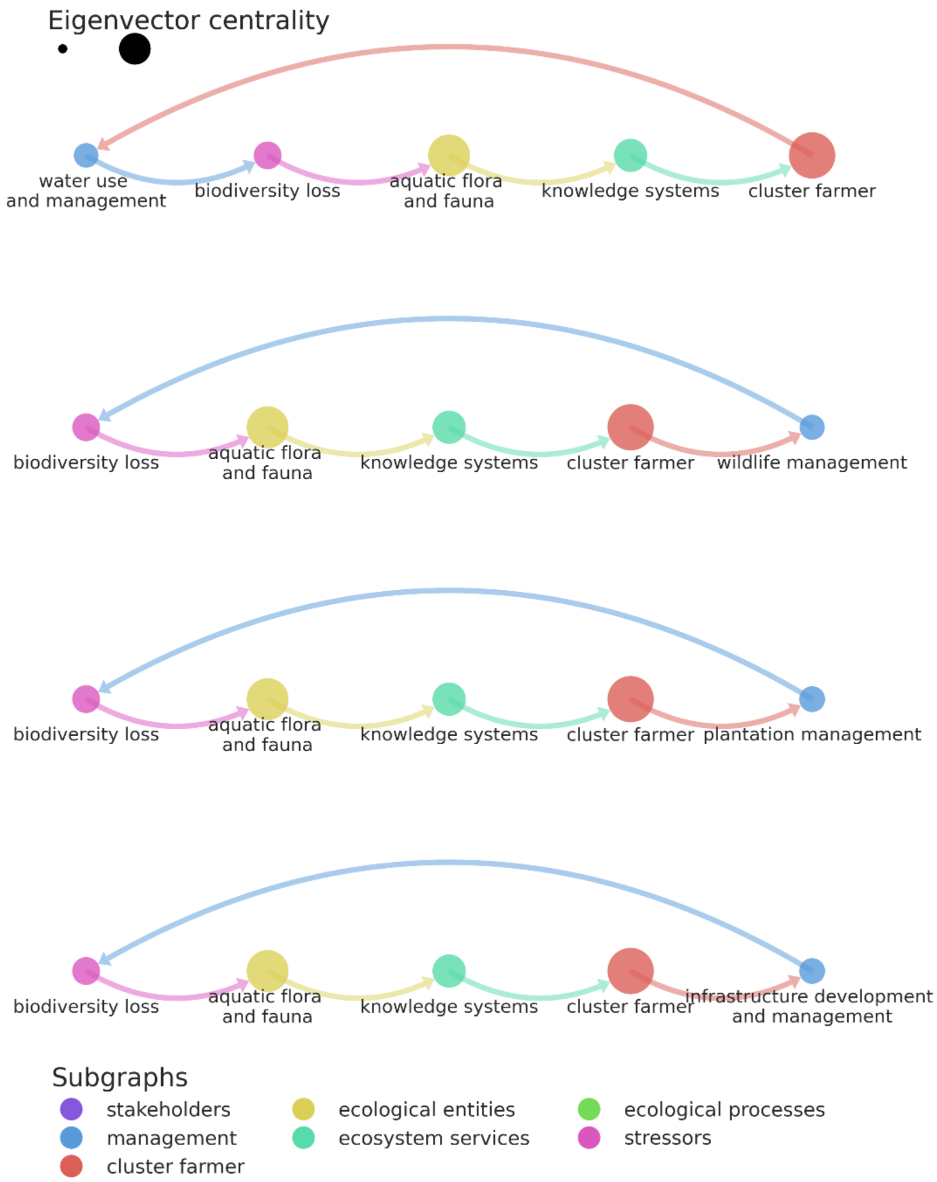

Figure 23. Cycles with the highest eigenvector centrality sum in the Scottish cluster. Cycles were selected from a pool of cycles that had a maximum length of 5.

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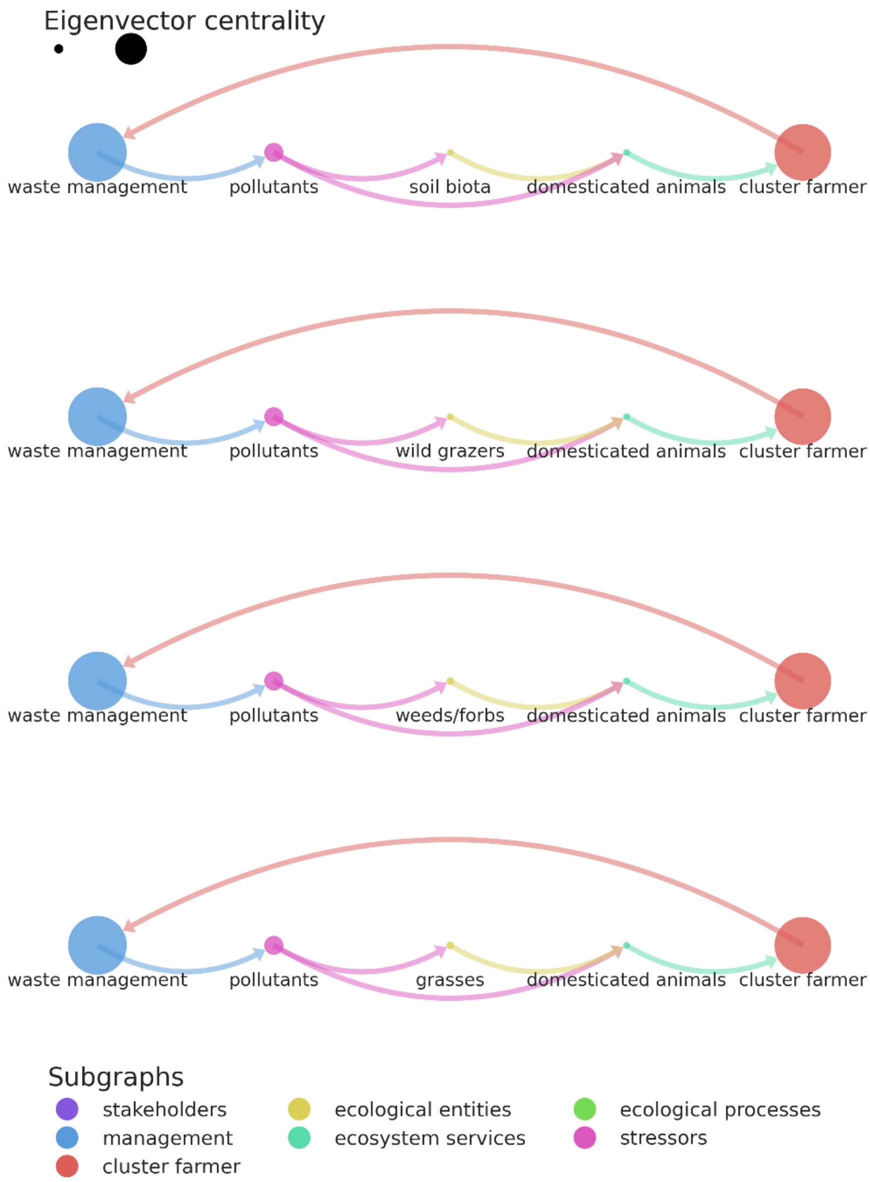

Figure 24. Cycles with the highest eigenvector centrality sum in the Italian cluster. Cycles were selected from a pool of cycles that had a maximum length of 5.

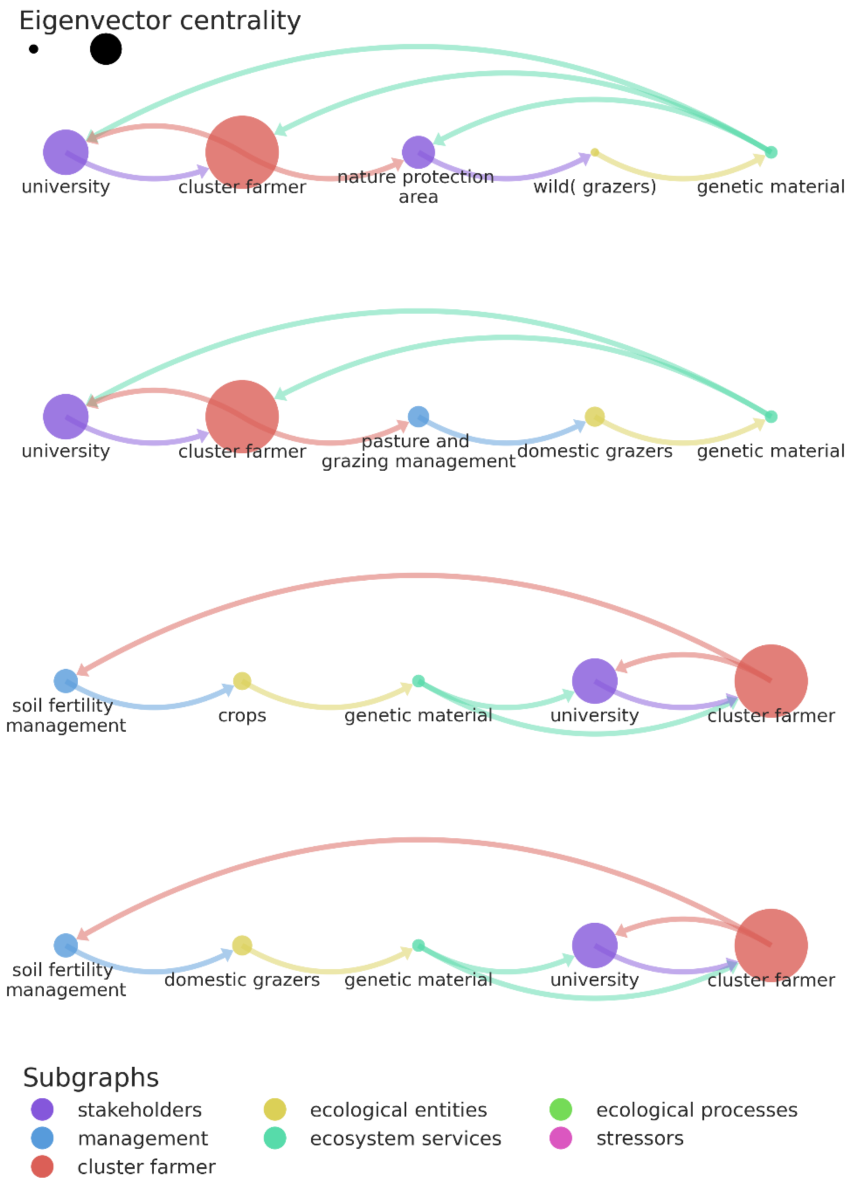

Figure 25. Cycles with the highest eigenvector centrality sum in the Luxembourgish cluster. Cycles were selected from a pool of cycles that had a maximum length of 5.

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6.6 Causal Loop Diagrams

6.6.1 Olive grove abandonment in the Italian system

In Figure 26, the Causal Loop diagram showing the interconnected causes of olive grove abandonment, ranging from economic and social factors to environmental pressures, set off a cascade of ecological consequences. Soil erosion, invasive species, and land degradation reduce the availability of diverse habitats, while increased fire risk poses a direct threat to species survival. Ultimately, the abandonment of olive groves transforms these semi-natural systems into degraded landscapes with diminished capacity to support diverse plant and animal life and biodiversity loss.

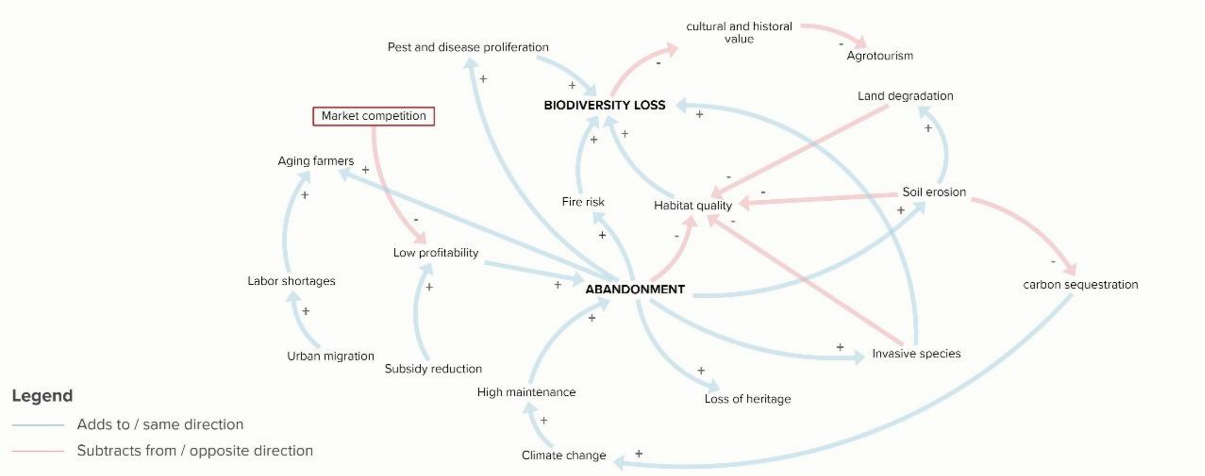

Figure 26. The causal loop diagram representing some system wide impacts of olive grove abandonment

6.6.2 Grazing livestock in pear and apple orchards in Luxembourg

Grazing livestock in pear and apple orchards presents both opportunities and challenges for the orchard ecology and ecosystem services as shown in Figure 27. Grazing helps manage undergrowth, control weeds, and prevent the spread of invasive species, but excessive grazing can lead to soil compaction and reduced soil fertility. It also supports biodiversity by providing habitats, although overgrazing may lower habitat quality. It also contributes to ecosystem services such as pollination, nutrient cycling, and pest control by maintaining ground cover, which helps prevent soil erosion. While grazing enhances soil health by adding organic matter and improving nutrient cycling, overgrazing can result in soil erosion and degradation, ultimately reducing orchard productivity. If not carefully regulated, it can lead to issues such as soil erosion and habitat degradation, thereby disrupting plant diversity and threatening overall productivity. Balancing these factors is crucial for optimising the social-ecological outcomes of integrating livestock into orchard systems.

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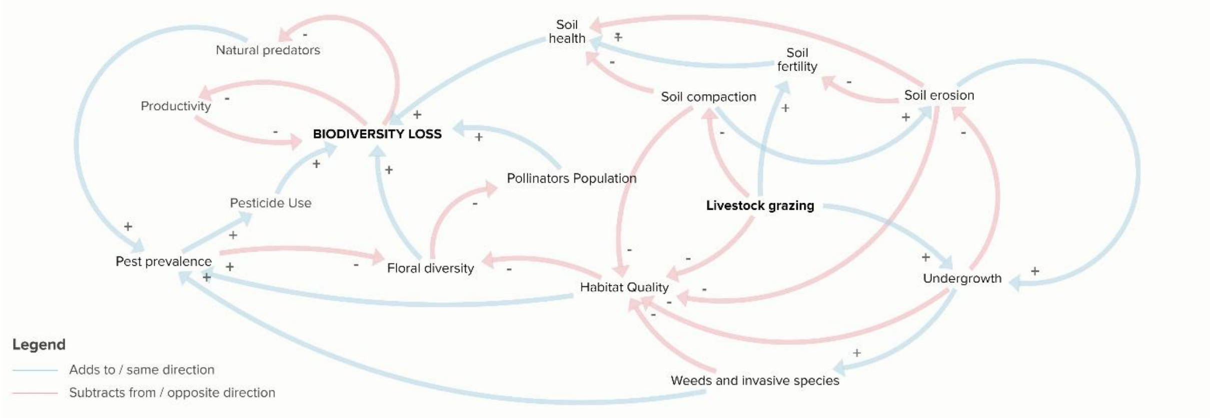

Figure 27. The causal loop diagram representing some system wide impacts of grazing in orchard

6.6.3 Field margins in the Scottish system

The introduction of flower margins can potentially mitigate the adverse effects of intensive farming, monocultures, and pesticide use on biodiversity. By increasing plant diversity, creating habitats for pollinators, and enhancing natural pest control, flower margins act as a positive intervention that reduces biodiversity loss in Scottish arable systems as shown in Figure 28. However, they may also cause habitat alteration and pest proliferation. On a systems level there is therefore a need to consider context-specific factors such as landscape configuration, other management practices, and potential unintended consequences.

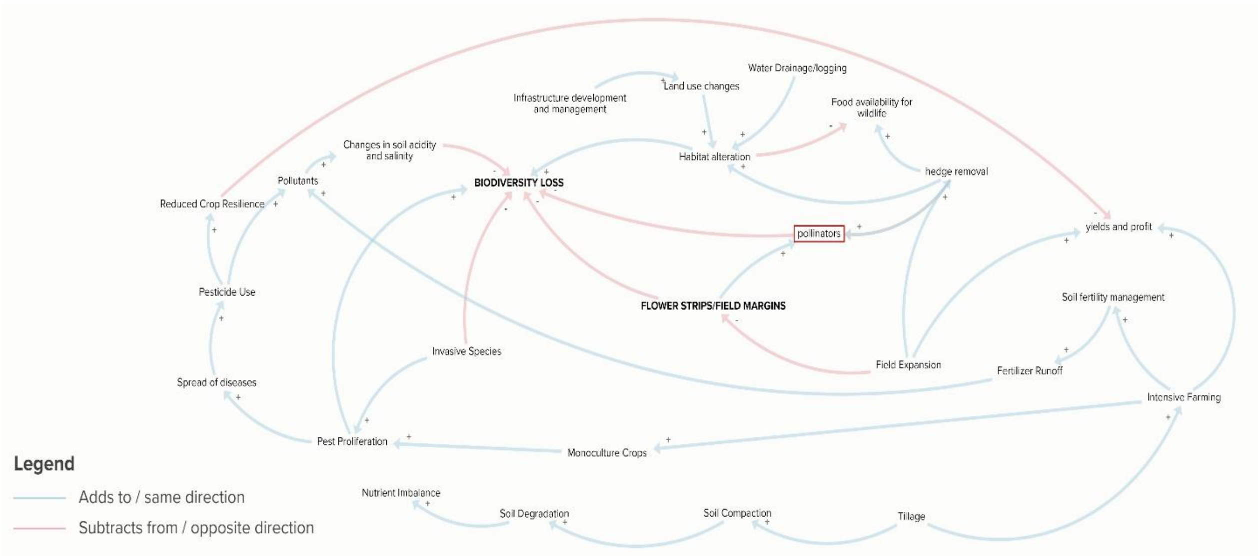

Figure 28. The causal loop diagram representing some system wide impacts flower strips in crop fields in the Scottish cluster

7. Discussion

Drivers and barriers to biodiversity-sensitive farming across various European agricultural systems can be framed around several key insights derived from the findings of this work. From the networks created for the three study sites, it is clear that agricultural social-ecological systems are highly

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connected and complex. As with complex systems, this means that they exhibit nonlinear interactions which need to be tracked to be able understand the ripple effects of change at some points of the network. The interconnectedness within these systems makes it critical to identify the main drivers and barriers that influence system behaviour, particularly in the context of biodiversity conservation in farming. Understanding these key elements allows the identification of potential levers that can enhance biodiversity, increase ecosystem resilience, and mitigate risks. By targeting these levers, we can more effectively manage and optimise the system, ensuring that interventions support both agricultural productivity and the preservation of biodiversity, which is essential for the long-term sustainability of farming systems.

Biodiversity sensitive farming integrates conservation with agricultural productivity, emphasising the role of biodiversity in enhancing ecosystem services, such as pollination, pest control, and nutrient cycling. These services are critical to buffering agricultural systems against environmental shocks (e.g. pest outbreaks, climate variability), but their provision is intricately tied to diverse biological communities (Bommarco et al., 2013). However, the adoption of biodiversity sensitive practices is not without its challenges, as farmers must navigate competing objectives, achieving sufficient income and long-term ecological integrity. One significant driver in promoting biodiversity sensitive practices is the growing recognition of the value of ecosystem services. Farmers, stakeholders, and policymakers increasingly understand that biodiversity can lead to sustainable farming outcomes by reducing dependency on external inputs (e.g. fertilisers and pesticides) and enhancing ecosystem resilience (Kremen & Miles, 2012). Social-ecological networks provide a framework for visualising how ecological entities, ecosystem services, management practices, and stakeholders interact within socio-ecological system (Sayles & Baggio, 2017). These networks demonstrate the interdependencies within farming systems and highlight the crucial role that farmers play as stewards of biodiversity.

Conversely, a major barrier to the wider adoption of biodiversity sensitive farming is economic pressure. Farmers often prioritise short term profitability over long term ecological benefits due to the immediate financial incentives tied to conventional farming practices. This is evident in systems like Italy's olive groves, where economic pressures have contributed to land abandonment. Such abandonment leads to cascading negative ecological impacts, including soil erosion, habitat degradation, and biodiversity loss (Guarino et al., 2019). This underlines the need for policy interventions that can realign financial incentives to reward practices that enhance ecosystem services and conserve biodiversity.

The centrality of policy frameworks and social actors in driving or hindering the implementation of biodiversity sensitive farming cannot be overstated. As revealed through network analyses, stakeholders such as government agencies, regulators, and local communities play a pivotal role in influencing farming decisions (Caulfield et al., 2020). In Scotland, for example, initiatives like the establishment of flower strips in arable fields have enhanced biodiversity by supporting pollinators and promoting natural pest control (Pywell et al., 2015). However, the success of such initiatives often hinges on collaborative, landscape scale management approaches, where farmers work collectively to implement biodiversity friendly practices (Power, 2010).

In Luxembourg, the grazing of livestock in orchards presents a complex interplay between ecological benefits and risks. While grazing can help control weeds and promote certain ecosystem services, overgrazing poses a threat to soil health and biodiversity (Danescu, 2010). Effective management in such contexts requires a nuanced understanding of the balance between promoting biodiversity and maintaining agricultural productivity.

Given that the network represents an extended 'supply-network' system, it is expected that the role of the farmers in the cluster is relevant given that they respond directly to the final demand of the 'consumer,' which is another important node. While the three systems exhibit some scale-free characteristics, the Val Graziosa and Buchan clusters are more topologically alike to each other than to the Born cluster. This can be noted when comparing the average degrees, and when observing the ranking of degrees. Contrasting the networks with other well studied networks like scale-free networks is relevant to derive insights of the systems' characteristics. More specifically, scale-free networks have special properties like the robustness against random failures (Albert & Barabási, 2002, Callaway et al., 2000) and they are like many types of real-world networks such as supply chain networks (Gao, et al 2016, Buldyrev et al 2000). Moreover, given that the networks are extensions of demand driven interactions (i.e. social--techno-ecological network), the presence of hubs and the degree distribution suggest that the network is far from being random, and the survey and network construction succeeded in capturing the supply network nature of the system (Thompson et al 2018, Newman et al 2003). The presence of hubs in both in and out-degree distributions put in evidence some fundamental characteristic of the systems. Based on the nature of the survey and network construction, the presence of hubs can be interpreted as if few nodes were 'consumers' of the rest of nodes, for the case of in-degree, and suppliers, for the case of out-degree. The fact that 'domestic grazers' and 'aquatic flora and fauna' have a higher eigenvector centrality among 'ecological entities' in the Born and Buchan clusters, respectively, indicates the intrinsic difference between orchards and a mixed crop-livestock. For Luxembourg, the network analysis of the social- ecological system, the nodes representing "university," "cluster farmers," and "genetic material" appear consistently across all identified cycles with the highest eigenvector centrality sum. This reflects the strong synergy and collaboration between the farmer clusters and the local research institution (labelled as "university") aimed at enhancing biodiversity and hence resulting in the provision of genetic material.

Through the causal loop diagrams the study provided valuable insights into the feedback mechanisms within farming systems. In systems like those in Luxembourg and Scotland, biodiversity loss was used as a reference mode to assess the impact of management practices such as grazing and the use of flower strips. These diagrams revealed how certain practices can either mitigate or exacerbate biodiversity loss, depending on their intensity and duration (Tscharntke et al., 2012). For example, olive grove abandonment in Italy, as explored through the CLDs, was shown to be a significant driver of biodiversity loss. The abandonment trend, fuelled by socio-economic factors, results in the degradation of both the agricultural and natural environments, highlighting the interconnectedness of economic and ecological systems (Venturi et al., 2017).

To identify opportunities and barriers for the design of policies, we focused on understanding the complexity of the interactions among nodes and on deriving insights and knowledge from their analysis rather than modelling and quantifying them explicitly. We opted for this strategy in order to (1) obtain general insights among the different systems rather than case-specific conclusions, and to (2) overcome the lack of detail in the relationships provided by the qualitative network model. In conclusion, the findings of this work suggest that while biodiversity sensitive farming offers a path toward more resilient and sustainable agroecosystems, its widespread adoption faces numerous barriers, especially economic and institutional ones. To overcome these, policy

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interventions must promote biodiversity through financial incentives, technical support, and the creation of farmer clusters that encourage collective action and knowledge sharing.

7.1 Limitations of the study

Social-ecological systems are characterised by dynamic interactions between many social and/or ecological components and for that reason it is not always possible to capture all the relevant entities and the interactions therein. Another challenge is that the systems are 'open' and may have interactions that go beyond geographical boundaries or the scope of the model more generally. Furthermore, the structural analysis of a network represents a snapshot of the system. Dynamic network analysis is possible and will be explored in coming work.

One of the key challenges in our analysis is that the identification of nodes and edges relied heavily on the expertise of local specialists, with final approval from the cluster facilitators in each region. While this method was essential for incorporating local knowledge and context, it also brings in a layer of subjectivity. What the experts identified, and what the facilitators approved, reflects their particular view of the clusters, which may not fully represent the objective reality of the systems we were studying. Instead of capturing the full complexity of the actual systems, the chosen nodes might reflect the personal priorities, experiences, and knowledge biases of the experts and facilitators regarding ecological processes, services, and stakeholders.

In other words, the final set of nodes might tell us more about how the experts and facilitators perceive these clusters than about the clusters' true structure and function. For instance, some important ecological processes or stressors might have been overlooked or downplayed if they weren't considered critical by the facilitators, even if they play a significant role in the system. Additionally, the rigor of the approval process likely varied from one cluster to another, depending on how familiar the facilitators were with the methodology or the scope of their local knowledge. This inconsistency could influence how nodes were selected, potentially affecting the comparability of the results across different regions. While the consistent identification of key ecological processes across clusters suggests there was a shared understanding of core dynamics, differences in other categories, such as ecosystem services or stakeholders, might reflect individual facilitators' perspectives rather than actual differences between regions.

8. Future research

Future research should continue to explore the complexities of social-ecological networks, employing both qualitative and quantitative approaches to deepen our understanding of the drivers and barriers to biodiversity sensitive farming across different agricultural contexts.

The next step will be to explore the implications of changes to some nodes on the overall network metrics (structure, function, and robustness). Changes on one or more components of the network can produce multiple results which may be either desirable or undesirable for the system. With the aim of improving biodiversity conservation, maintaining, or improving productivity there are various management or policy options that the system can be exposed to. This includes both internal (within network) and external (outside network e.g. policies and climate change) factors. Nevertheless, conventional approaches designed to conduct such analysis (e.g. closeness vitality (Brandes, 2005))

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are not suitable for highly heterogeneous systems likes the ones described in the three networks. To overcome this, we propose to model these changes through simulation methods in order to assess the implications of perturbations on network stability and general performance. In fact, this approach of modelling directly contributes to Task 7.4, in which simulations methods such as Agent Based Modelling are being using to understand complex interactions in the systems. Some of the research questions that will be addressed in the following steps include:

- How do changes on one part of the system (farm level/change in practice or management) affect other parts, over time?
- What are the potential impacts or unintended consequences of interventions for different social actors?

9. Policy implications/recommendations

This section explores potential considerations for agricultural policy based on the findings of the socio-ecological network analysis across the three European farming systems studied. While the results offer valuable insights into the interactions between ecological entities, stakeholders, and management practices, they do not directly prescribe specific policy actions. Instead, they highlight areas where more nuanced, integrated approaches to agricultural and biodiversity management could be beneficial. By reflecting on these findings, this section outlines possible policy directions that, while not conclusive, may support the broader objectives of sustainable farming and biodiversity conservation.

Intergrated/Network-based agricultural management- The analysis reveals that ecological entities and stakeholders are closely intertwined within different agricultural systems (Scotland, Italy, Luxembourg). A possible policy consideration could be to encourage more collaborative and systems thinking approaches to farm management. While the findings do not definitively recommend specific policy interventions, the interconnectedness between farmers, stakeholders, and ecological processes imply that more integrated, multi-stakeholder frameworks may support biodiversity-sensitive farming practices at a landscape scale.

Localised management practices- The varying topologies and drivers across different clusters (e.g., livestock grazing in Luxembourg, olive groves in Italy) suggest that localised solutions might be more effective in managing biodiversity. Policies could subtly aim at tailoring biodiversity initiatives to specific ecological and social contexts, rather than applying one-size-fits-all approaches. While the evidence doesn't make an outright call for this, the uniqueness of stressors and practices across regions might benefit from context specific policy frameworks.

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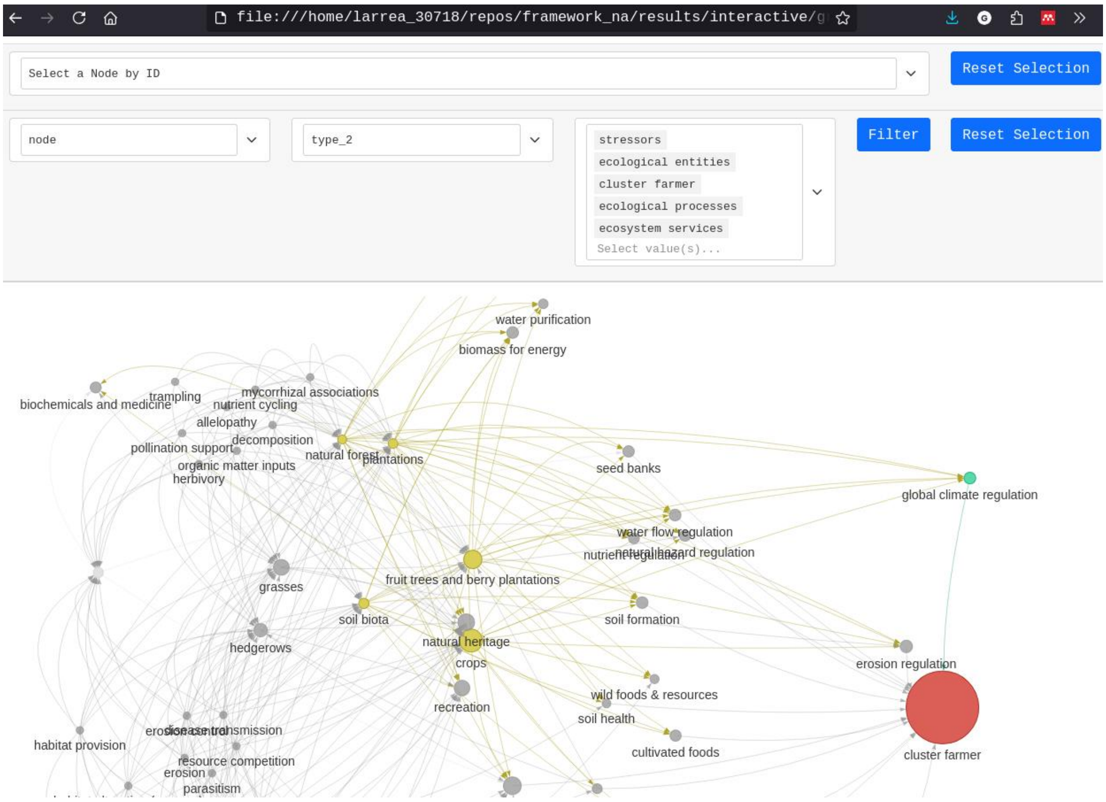
Appendix

Annex (i) Screenshot of the usage of the web tool to visualise the three resulting networks. The tool allows to filter, highlight and explore networks at detail.



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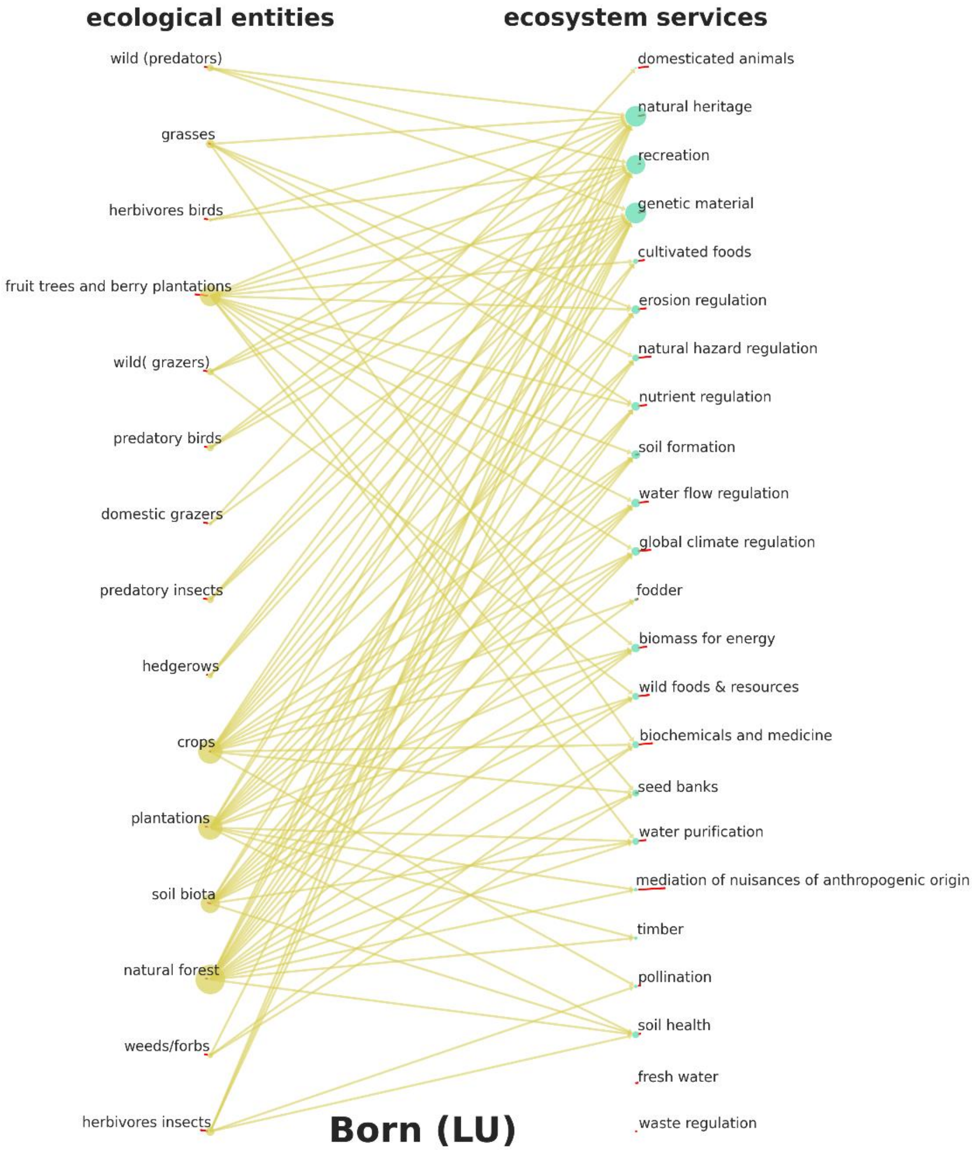
Annex (ii) Inter-layer interactions between ecological entities and ecosystem services. Nodes' sizes are proportional to their out-degree centrality in the left side and in-degree centrality in the right side.



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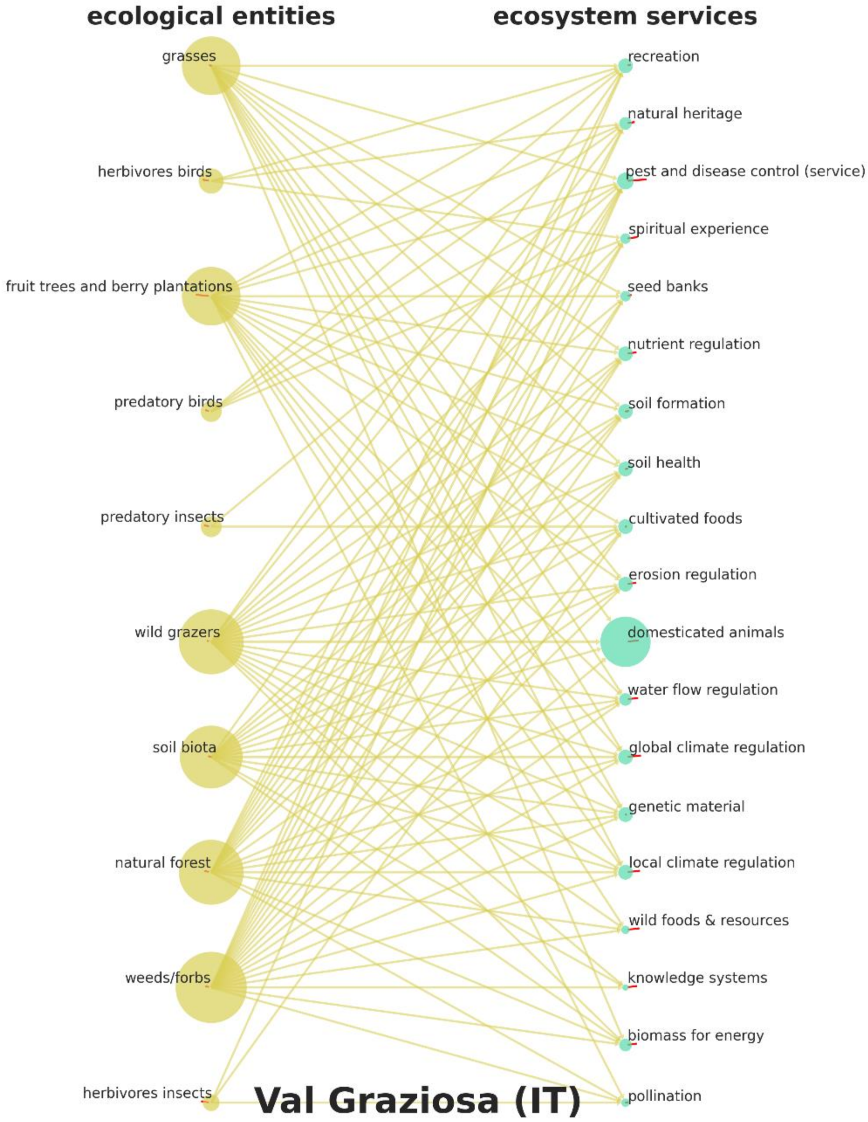
Annex (iii) Inter-layer interactions between ecological entities and ecosystem services. Nodes' sizes are proportional to their out-degree centrality in the left side and in-degree centrality in the right side.



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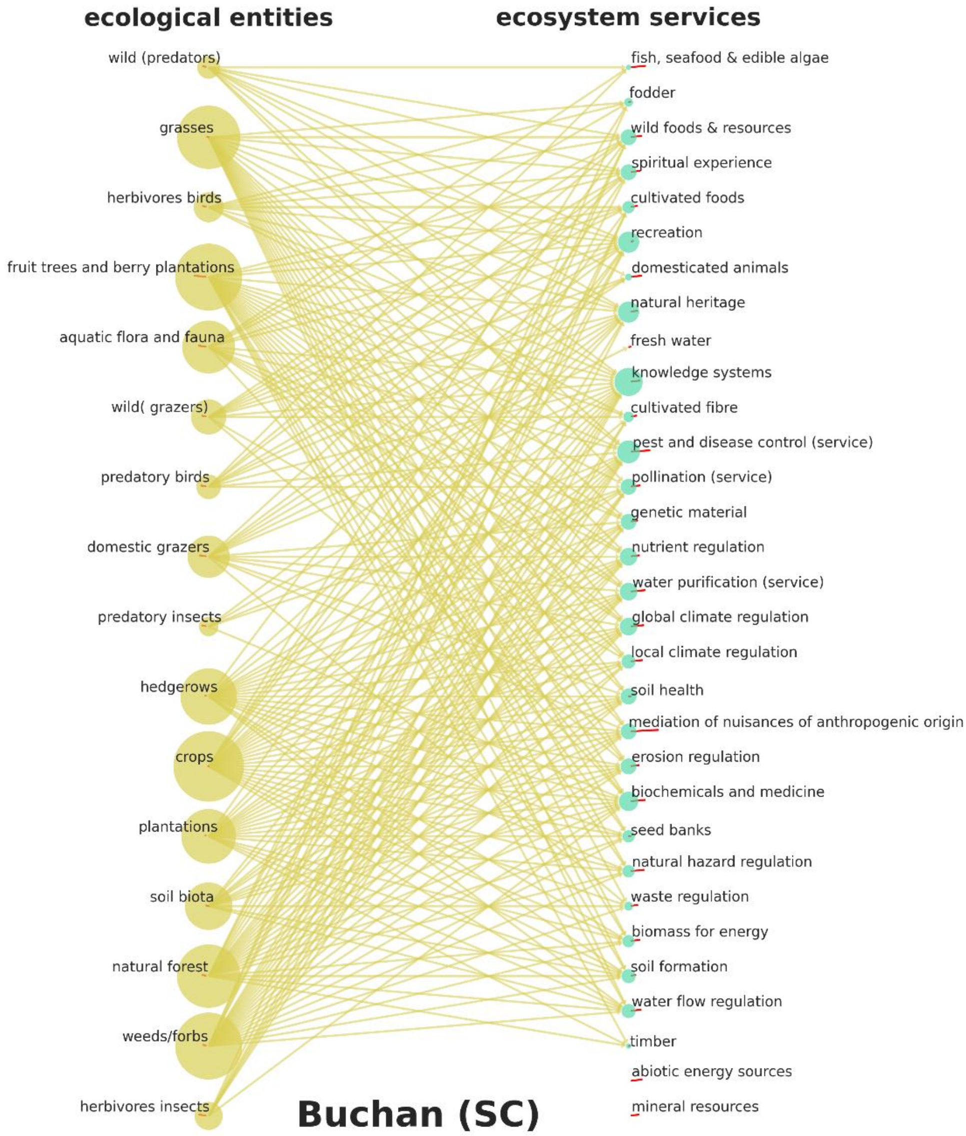
Annex (iv) Inter-layer interactions between ecological entities and ecosystem services. Nodes' sizes are proportional to their out-degree centrality in the left side and in-degree centrality in the right side.



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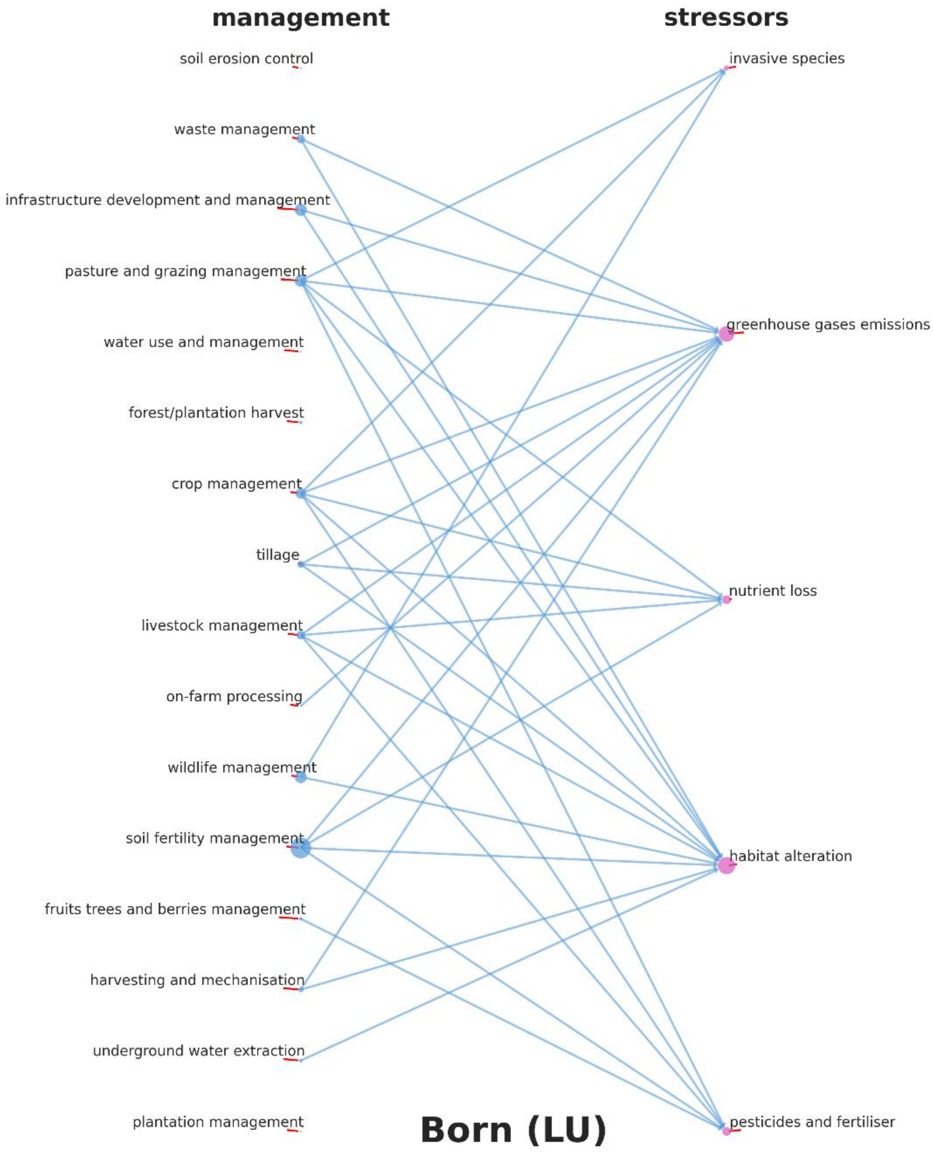
Annex (v) Inter-layer interactions between management and stressors. Nodes' sizes are proportional to their out-degree centrality in the left side and in-degree centrality in the right side.



Annex (vi) Inter-layer interactions between management and stressors. Nodes' sizes are proportional to their out-degree centrality in the left side and in-degree centrality in the right side.

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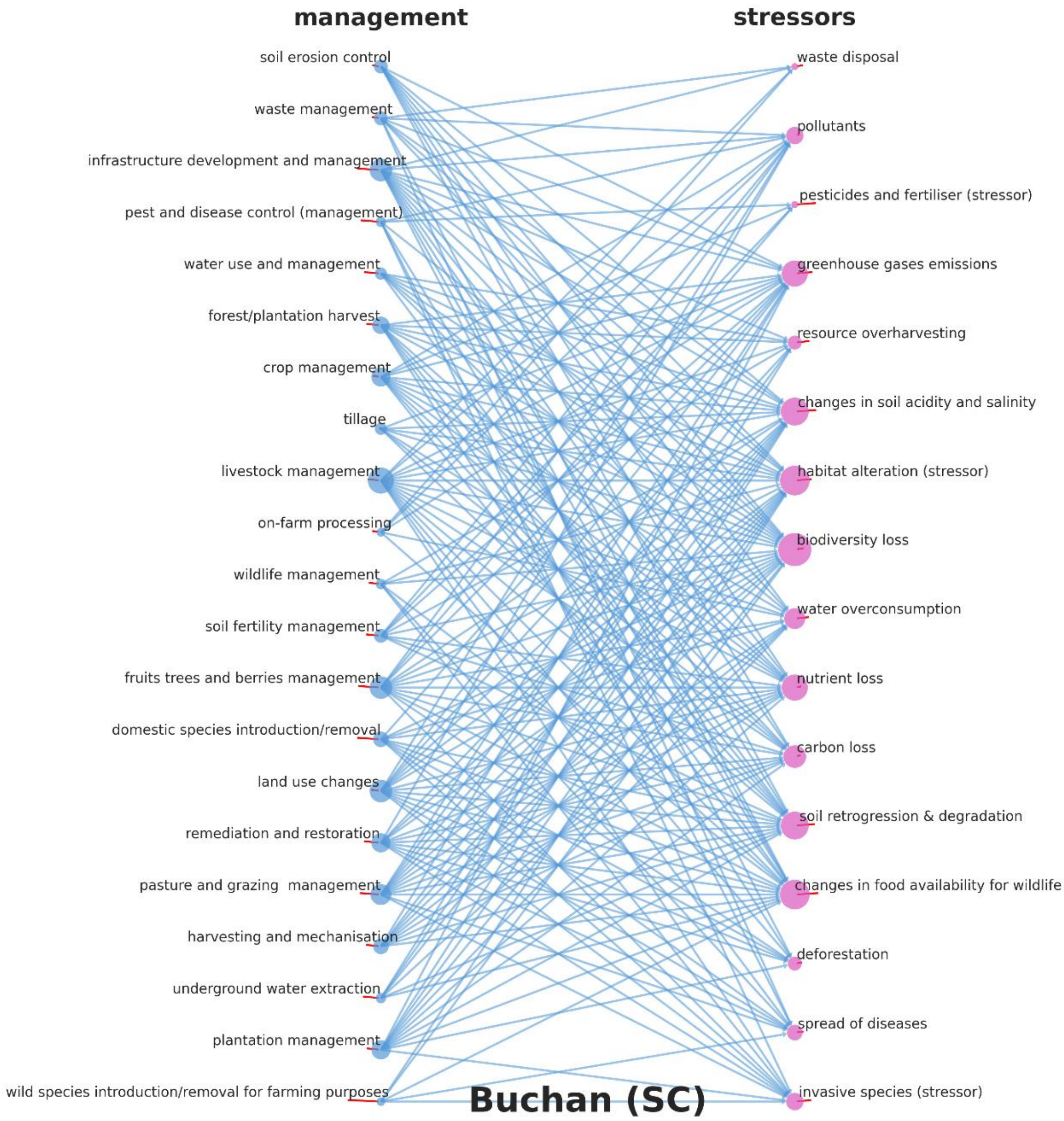
Annex (vii) Inter-layer interactions between management and stressors. Nodes' sizes are proportional to their out-degree centrality in the left side and in-degree centrality in the right side.



Annex (viii) Inter-layer interactions between stakeholders and farmer's cluster. Nodes' sizes are proportional to their out-degree centrality in the left side and in-degree centrality in the right side.

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Annex (ix) Inter-layer interactions between stakeholders and farmer's cluster. Nodes' sizes are proportional to their out-degree centrality in the left side and in-degree centrality in the right side.

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Annex (x) Inter-layer interactions between stakeholders and farmer's cluster. Nodes' sizes are proportional to their out-degree centrality in the left side and in-degree centrality in the right side.

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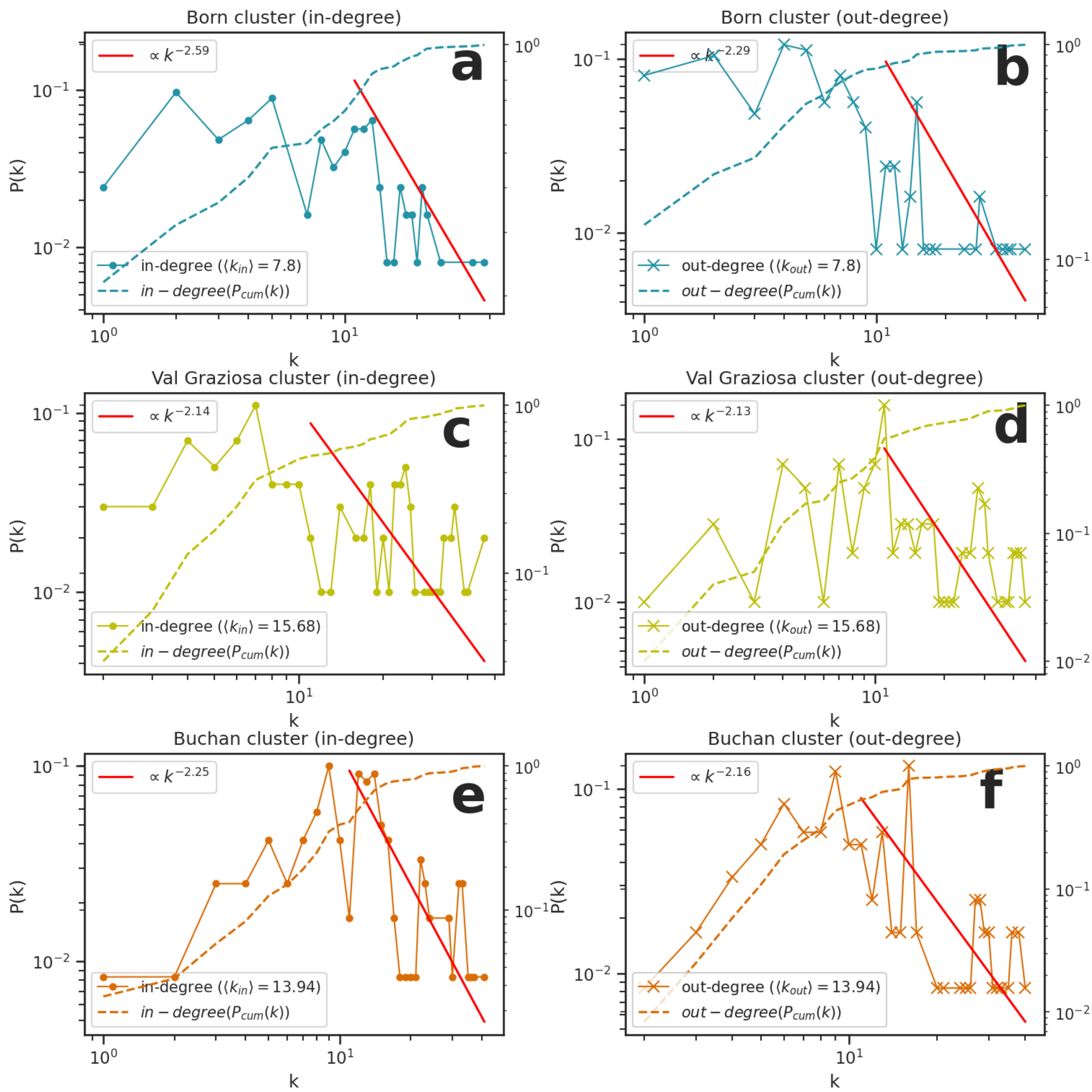
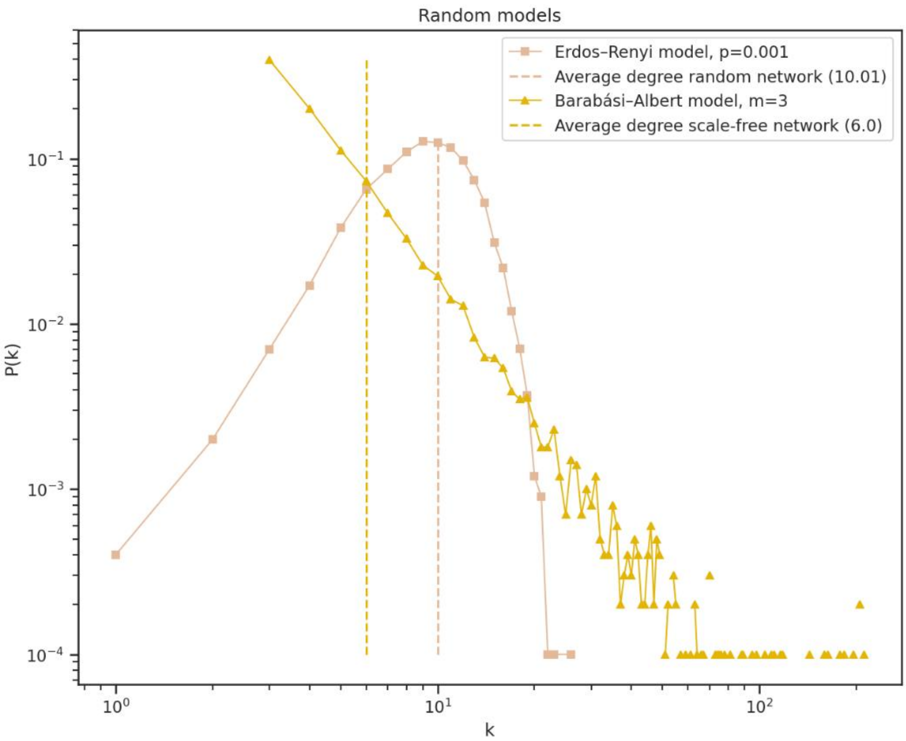
Annex (xi) In and out –degree distributions for the Born (a and b, respectively), Val Graziosa (c and d, respectively), and Buchan (e and f, respectively) systems. The continuous line indicates the probability distribution, and the dashed line shows the cumulative probability. For each case, the distribution was fit to a power law distribution to obtain an alpha parameter. Scale-free networks have an alpha value between 2 and 3.



Annex (xii) Degree distribution of the Erdos-Renyi and the Barabasi-Albert models. The Erdos-Renyi model generates a random network, while the Barabasi-Albert model generates a network with scale free properties. In random networks, the degree distribution has a short tail, and it is distributed around the average degree. In scale-free networks, the degree distribution has a long tail, nodes with few connections are abundant, and few nodes are considerably more connected than the average (i.e., hubs).



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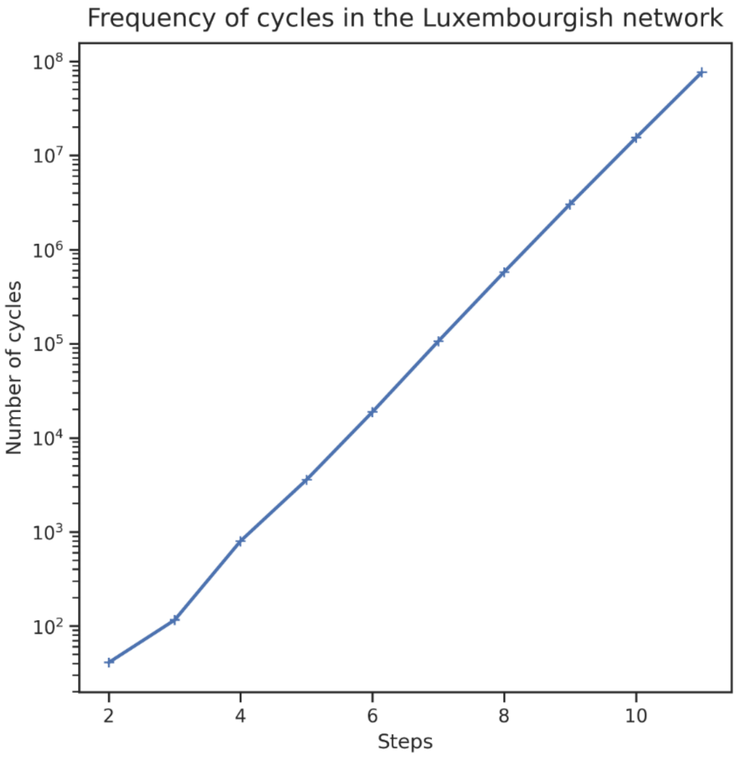
Annex (xiii) Frequency of cycles identified in the Luxembourgish network for 2 to 10 steps. The number of cycles increases in an exponential fashion the more steps are considered in the algorithm.



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Annex (xiv) Comparison of nodes across the three clusters: Green indicates a node that exists in the cluster, while red indicates a node that does not exist in the cluster.

		Born	Buchan	Val Grazlosa
Ecological entities	Aquatic flora and fauna	Red	Green	Red
	Crops	Green	Green	Red
	Domestic grazers	Green	Green	Red
	Fruit trees and berry plantations	Green	Green	Green
	Grasses	Green	Green	Green
	Hedgerows	Green	Green	Red
	Herbivores birds	Green	Green	Green
	Herbivores insects	Green	Green	Green
	Natural forest	Green	Green	Green
	Plantations	Green	Green	Red
	Predatory birds	Green	Green	Green
	Predatory insects	Green	Green	Green
	Soil Biota	Green	Green	Green
	Weeds/forbs	Green	Green	Green
	Wild (predators)	Green	Green	Red
	Wild grazers	Green	Green	Green
Ecological processes	Allelopathy	Green	Green	Green
	Decomposition	Green	Green	Green
	Disease transmission	Green	Green	Green
	Erosion	Green	Green	Green
	Erosion control	Green	Green	Green
	Food source	Green	Green	Green
	Habitat alteration (process)	Green	Green	Green
	Herbivory	Green	Green	Green
	Invasive species spread	Green	Green	Green
	Mycorrhizal associations	Green	Green	Green
	Nutrient cycling	Green	Green	Green
	Organic matter inputs	Green	Green	Green
	Parasitism	Green	Green	Green
	Pest and disease control	Green	Green	Green
	Pollination support	Green	Green	Green
	Predation	Green	Green	Green
	Resource competition	Green	Green	Green
	Trampling	Green	Green	Green
	Water contamination	Green	Green	Green
	Water purification	Green	Green	Green
Ecosystem services	Abiotic energy sources	Red	Green	Red
	Biochemicals and medicine	Green	Green	Red
	Biomass for energy	Green	Green	Green
	Cultivated fibre	Red	Green	Red
	Cultivated foods	Green	Green	Green
	Domesticated animals	Green	Green	Green
	Erosion regulation	Green	Green	Green
	Fish, seafood & edible algae	Red	Green	Red
	Fodder	Green	Green	Red
	Fresh water	Green	Green	Red
	Genetic material	Green	Green	Green
	Global climate regulation	Green	Green	Green
	Knowledge systems	Red	Green	Green
	Local climate regulation	Red	Green	Green
	Mediation of nuisances of anthropogenic origin	Green	Green	Red
	Mineral resources	Green	Red	Red
	Natural hazard regulation	Green	Green	Red
	Natural heritage	Green	Green	Green
	Nutrient regulation	Green	Green	Green
	Pest and disease control	Green	Green	Green
	Pollination	Green	Green	Green
	Recreation	Green	Green	Green
	Seed Banks	Red	Red	Green
	Soil formation	Green	Green	Green
	Soil Health	Green	Green	Green
	Spiritual experience	Red	Green	Green
	Timber	Green	Green	Red
	Waste regulation	Green	Green	Red
	Water flow regulation	Green	Green	Green
	Water purification	Green	Green	Red
	Wild foods & resources	Green	Green	Green
Management	Crop management	Green	Green	Red
	Domestic species introduction/removal	Red	Green	Red
	Fertilization	Red	Red	Green
	Forest/plantation harvest	Green	Green	Red
	Fruits trees and berries management	Green	Green	Red
	Green cover	Red	Red	Green
	Harvesting and mechanisation	Green	Green	Red
	Infrastructure development and management	Green	Green	Red
	Land use changes	Red	Green	Red
	Livestock management	Green	Green	Red
	Mechanical harvesting	Red	Red	Green
	On-farm processing	Green	Green	Green
	Pasture and Grazing Management	Green	Green	Green
	Pests and disease control (management)	Red	Red	Green
	Plantation management	Green	Green	Red
	Remediation and restoration	Red	Green	Red
	Soil erosion control	Green	Green	Green
	Soil fertility management	Green	Red	Green
	Tillage	Green	Green	Red
	Tree pruning	Red	Red	Green
	Underground water extraction	Green	Green	Red
	Waste management	Green	Green	Green
	Water use and Management	Green	Green	Red
	Wild species introduction/removal for farming purposes	Green	Red	Red
	Wildlife management	Green	Green	Green
Stakeholders	Agricultural agencies and administration	Red	Red	Green
	Agricultural agencies and administration	Green	Red	Red
	agricultural agencies (subsidies)	Green	Red	Red
	Agricultural associations	Green	Green	Green
	agriculture administration	Green	Red	Red
	Agronomists	Green	Red	Green
	Banks	Green	Red	Green
	Buyers and Distributors	Red	Green	Red
	Cluster farmers	Green	Green	Green
	Compost suppliers	Green	Red	Green
	environment agencies	Green	Red	Red
	environmental administration	Green	Red	Red
	Environmental Organizations	Green	Green	Green
	Exporters	Red	Red	Green
	Farmer organizations promoting sustainable farming	Green	Red	Green
	Feed suppliers	Green	Red	Red
	Fertilizers suppliers	Green	Red	Green
	Financial institutions	Red	Green	Red
	Forest administration	Green	Red	Green
	Fruit transformers	Green	Red	Green
	Government Agencies and Regulators	Red	Green	Red
	Grain merchants	Green	Red	Red
	Grain transformers	Green	Red	Red
	Impact investors / sustainable finance	Red	Red	Green
	Industry sustainability NGO	Green	Red	Green
	Investors and shareholders	Red	Green	Red
	Labelling agencies	Green	Green	Red
	Labour force	Green	Green	Green
	Local communities	Green	Green	Green
	Local/regional council	Green	Red	Green
	Logistics	Red	Red	Green
	Milk tranformers	Green	Red	Red
	Mills	Red	Red	Green
	Nature protection agencies	Green	Red	Red
	Nature protection area	Green	Red	Red
	Other farms	Green	Green	Red
	Non-departmental public bodies	Green	Green	Green
	Organic nurseries	Green	Red	Red
	Private customers	Green	Red	Green
	Private landowners (renting out land)	Green	Red	Green
	Property management companies	Red	Red	Green
	Renewable energy providers	Green	Red	Green
	Research and Education Institutions	Green	Red	Red
	Retail organizations	Green	Red	Red
	Retailers	Green	Red	Green
	Rural development agencies	Green	Red	Green
	Schools	Green	Red	Green
	Seed sellers	Green	Red	Red
	Suppliers and Service Providers	Red	Green	Red
	Tourism and Visitors	Green	Green	Green
	Tourism promotion associations	Red	Red	Green
	Trader- agents	Green	Red	Red
	Trader-supplier agents	Green	Red	Red
	Transportation and Logistics Providers	Red	Green	Red
	Universities	Green	Red	Green
	Water utility companies	Green	Red	Red
	wildlife and hunting NGOs	Green	Red	Green
	Wildlife Conservation Organizations	Red	Green	Red
	Youth associations	Green	Red	Green
Stressors	Biodiversity loss	Red	Green	Green
	Carbon loss	Red	Green	Red
	Changes in food availability for wildlife	Red	Green	Red
	Changes in soil acidity and salinity	Red	Green	Red
	Deforestation	Red	Green	Red
	Greenhouse gases emissions	Green	Green	Green
	Habitat alteration (stressor)	Green	Green	Red
	Invasive species	Green	Green	Green
	Nutrient loss	Green	Green	Red
	Pesticides and fertiliser	Green	Green	Green
	Pollutants	Red	Green	Green
	Resource overharvesting	Green	Red	Red
	Soil retrogression & degradation	Red	Green	Red
	Spread of diseases	Red	Green	Red
	Waste disposal	Red	Green	Green
	Water overconsumption	Red	Green	Red

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