Stakeholders analysis and engagement to address Water-Ecosystem-Food Nexus challenges in Mediterranean environments: a case study in Italy

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Highlights

- *Agroecosystem sustainability requires overcoming siloed management approaches to water, environment, and food resources.*
- *An integrated methodological framework was developed to address Nexus interlinkages and trade-offs by participatory multi-actor approaches.*
- *Systematic methodologies were applied for Stakeholder Analysis and to develop multi-domain participatory tools for knowledge sharing*
- *Stakeholder Mapping, Learning and Action Alliance and Participatory System Dynamic Modelling for collaborative learning were implemented at a pilot scale.*
- *Understanding cross-sectoral dynamics and behaviors improved Nexus framing and broadened agreement on management solutions for sustainability.*

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Key words: stakeholder mapping; learning and action alliance; participatory approach; resource management innovation; causal loop diagram; sustainability.

Funding/acknowledgments: the authors acknowledge the project LENSES, which has received funding from the PRIMA Programme supported by the European Union.GA n°2041 (LENSES). This paper and the content included in it do not represent the opinion of PRIMA Foundation, PRIMA Foundation is not responsible for any use that might be made of its content.

Contributions: BV, VS, PA, BM, conception and design, analysis and interpretation of data; BV, VS, PA, BM, PT, GR, PI, LME, drafting the article or revising it critically for important intellectual content. FS, ADF and all authors approved the final version to be published.

Received: 12 February 2023.
Accepted: 25 October 2023.
Early view: 25 October 2023.

Italian Journal of Agronomy 2023; 18:2200
doi:10.4081/ija.2023.2200

Abstract

The Water-Ecosystem-Food Nexus is a powerful framework developed for analyzing complex interlinkages among natural resource domains and overcoming "siloed" management practices. Multi-actor participatory approaches are increasingly recognized in Nexus research as the most effective way to identify trade-off solutions between divergent interests. Despite this acknowledged potential, the active engagement of stakeholders for the co-creation of knowledge is still limited to date, missing the opportunity for innovation processes and policy designs to be grounded in context-specific knowledge and experiences.

This paper outlines the methodological framework developed to integrate stakeholder analysis and participatory tools for exploring Nexus challenges in a pilot area in Tarquinia, Italy, where a multi-stakeholder group was set up encompassing several categories at different levels, from policymakers and authorities to farmers and other end users. Systematic methodologies to target, analyze, and actively engage stakeholders were applied and multi-domain participatory tools were developed, *i.e.*, Stakeholder Analysis and Mapping, Learning and Action Alliance, Participatory System Dynamic Modelling, which broaden the agreement on potential locally-tailored solutions for sustainable farming practices and integrated management of natural resources. Mutual learning activities, tapping into actors' deep understanding of specific local dynamics, served to better frame the complexity of the Nexus and build a common understanding of local societal challenges as well as of potential innovations in farming practices, land, and water management. The methodological innovation of integrating stakeholder mapping and analysis with relevant spatial information from participatory activities, provides the fundamental baseline for spatially explicit scenario analysis in the area, ultimately increasing the relevance and transferability of the Nexus findings.

Introduction

The concept of sustainability of agroecosystems is a cross-sectoral challenge as it involves managing agri-environmental resources in a way that ensures economic productivity while maintaining and restoring ecosystems and minimizing climate change impacts. However, the policy agenda often fails to consider the complex interlinkages between key resource domains, and as a consequence, decision-makers fail to meet in their strategies the request for integrated and sustainable allocation of limited resources (WEF, 2015). Persistent science-to-policy gaps led over time to a widely recognized lack of decision support tools that include all actors at the multi-scale level; thus, overlooking the multiple underlying mechanisms influencing resource management from the local to regional, national, or global level (Barraclough *et al.*, 2022). In this regard, the Nexus was developed as a powerful research framework for analyzing the complex interlinkages among key resource domains to help address global societal challenges such as water scarcity, food security/sustainability, ecosystem conservation/restoration, and climate change (Flammini *et al.*, 2014; Kurian and Ardakanian, 2015; Mohtar and Daher 2016).

The concept behind the Nexus relies on the resolution of conflicts and negotiation of collaboration between usually compartmentalized realms ("siloed" resource management) to develop innovative management strategies and decision support tools (Hagemann and Kirschke, 2017; Howarth and Monasterolo, 2016; Pahl-Wostl, 2019). To this aim, stakeholder involvement and multi-actor approaches are increasingly recognized in Nexus research as the most effective way to identify interdependencies and suitable solutions (such as policies or technical innovations) in view of multiple divergent interests and potential trade-offs (Hoolohan *et al.*, 2018; Sušnik and Staddon, 2021). The adoption of participatory approaches for the co-creation of knowledge can bridge the gap between academic research and the expertise of non-academic actors operating in practice across water-ecosystems-food (WEF) systems, as well as facilitate the dialogue among science and policy realms. To increase the impact of research and develop an effective policy response, scientific support might no longer be sufficient, as it requires the coordination, support, commitment and understanding of all decision-makers (Albrecht *et al.*, 2018; Melloni *et al.*, 2020; Reed *et al.*, 2009). This is particularly crucial in a Nexus framework, where a participatory approach can help unveil synergies and the different competing factors of the complex reality of the WEF system. Stakeholder analysis enables the identification of the main actors and the assessment of their interests in the system. Stakeholder active engagement tools can help facilitate collaboration, *e.g.*, by integrating local knowledge and perceptions of the investigated problem, therefore serving as a tool to support decision-making and strategy formulation (*e.g.*, Coletta *et al.*, 2021; Scrieciu *et al.*, 2021; Winz *et al.*, 2009). Several studies report an increased understanding and better framing of the Nexus, as well as greater agreement on potential solutions for resource management (Sušnik *et al.*, 2018; Tidwell *et al.*, 2016). This not only increases the relevance of the Nexus research but also fosters consensus on innovations that in turn promote and enable the effective adoption of integrated policy recommendations in the Nexus space (Hurley *et al.*, 2022). Howarth and Monasterolo (2016) applied a transdisciplinary approach to knowledge co-production for decision-making processes on building resilience to climate shocks along the Nexus, by means of workshops with stakeholders from academia, government, and industry. Hoolohan *et al*. (2018) provided insights of Nexus projects aimed explicitly at including non-academic stakeholders as co-creators of knowledge. Their understanding of Nexus-related challenges had a material impact on the research relevance and, for example, enabled the research team to successfully connect qualitative insights with quantitative model outputs. Despite this acknowledged potential, it is still uncommon for stakeholders to become active partners in Nexus research.

In most cases, they are considered merely end users, preventing innovation processes and policy designs from incorporating context-specific knowledge and experiences (Albrecht *et al.*, 2018; Galaitsi *et al.*, 2018; Markantonis *et al.*, 2019; Schinko *et al.*, 2022). Likewise, Nexus research is sometimes done without considering the operating space of decision-makers, largely constrained by regulations and limited resources. The identification and selection of stakeholders are often done on an *ad hoc* basis, which can lead to the exclusion of important groups, bias of results, and jeopardize the long-term sustainability of the research (Horlings *et al.*, 2020; Reed *et al.*, 2009). According to the findings of Howarth and Monasterolo, (2017), in Nexus research more knowledge is needed specifically on the behavior of cross-sectoral stakeholders and on their potential reaction to the impacts of Nexus disturbances (*e.g.*, climate change) or innovations (*i.e.*, mitigation and adaptation policies). In turn, to deepen our knowledge of stakeholder behavior, it is necessary to determine the direction, intensity, and potential effect of their network of relationships within the Nexus, as well as their perceived gains and losses on their activities within the Nexus.

This paper is the result of innovative research addressing participatory approaches in Nexus research as the most effective way to identify interlinkages between different natural resource domains. The work has been conducted as part of a broader research context, that includes seven pilot areas across the Mediterranean, one of the most vulnerable areas to climate change. All focus on the competitive uses of water and land resources for farming practices, conservation of natural ecosystems, and other activities related to natural resource use, such as tourism or industrial production. The results of the latest Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2022) show that the Mediterranean area will have to face particularly significant impacts in the coming decades linked to rising temperatures, an increased frequency of extreme events (drought, heat waves, heavy rainfall) and the reduction and change in the rainfall regime on a seasonal or annual scale. Agricultural activities and the economy may be irreversibly damaged by the severe weather patterns caused by climate change. At a time when about 70% of freshwater is consumed in agriculture globally and water demand is increasing twice as fast as population growth, agriculture is called upon to meet the economic and social challenges of increasing food demand and rising competition for dwindling resources such as water and soil (Baratella and Trinchera, 2018 and references therein). These pressures will be compounded by an increase in extreme weather events, due to climate change.

The pilot area of Tarquinia, which is the subject of this study, represents typical Mediterranean conditions in terms of climate change impacts, surface and groundwater interaction, potentially competing resource uses, and the importance of agricultural activities. Under such conditions, the application of a participatory approach can help local actors shape the expected transition to sustainable development goals and the necessary management strategies (Barraclough *et al.*, 2022; Ciaccia *et al.*, 2021; Norstrom *et al.*, 2020). Involving all relevant parties in decision-making, taking into account the needs and interests of all stakeholders, is the basis for exploring deeper governance issues and fostering collaboration and collective learning across the identified domains to co-design and test management solutions that are able to cope with changes and disturbances, leading to the development of resilient agro-environmental systems (Ciaccia *et al.*, 2019; Duru and Therond, 2015). This paper outlines methodologies and tools developed to implement a participatory process investigating Nexus-related challenges in the pilot area of Tarquinia (Italy), and how they were integrated to target, analyze and actively engage stakeholders. We explain how to connect contextual insights into the Nexus space, which ultimately will increase the relevance and transferability of the research findings for the development and implementation of locally tailored policy recommendations on a range of different scales. The innovative, added value of this analysis is the development of a methodological framework to identify, map, and actively involve stakeholders in: i) the analysis of the system state and potential evolution; ii) the definition of strategies aimed at tackling potential economic, social and environmental challenges related to the management of natural resources under climate change. The present work also underlines the importance of raising stakeholder awareness on the tight interconnectedness of multiple domains and the multidimensional impacts associated with the adoption of innovations in farming practices, land and water management. To bring to light the complex, non-linear interactions among the different elements that characterize water-environment-food systems at a local level, a multi-stakeholder group was set up encompassing several categories at different levels, from policymakers and regulatory authorities, to farmers, non-governmental organizations (NGOs), and other end users. Combining scientific approaches with stakeholder knowledge led to a shared, deeper understanding of societal challenges and broadened the agreement on potential solutions for sustainable and integrated natural resource management. Furthermore, the proposed approach guarantees replicability in all contexts where common and interconnected issues must be solved through shared participatory solutions.

Materials and Methods

Methodological framework

Research into the complex reality of natural resource systems requires a continuous dialogue between researchers and stakeholders. This awareness underlies the methodological approach of the present work, which develops and implements a participatory process to investigate Nexus-related challenges in the pilot area of Tarquinia (Italy), as part of a broader research context that includes seven pilot areas representative of the key physical and agricultural features of the Mediterranean basin (Tarquinia Plain in Italy, Plinios Basin and Koiliaris Critical Zone in Greece, Gediz Basin in Turkey, Doñana region in Spain, Hula Valley in Israel and Middle Jordan Valley in Jordan). The establishment of a local multi-stakeholder group, from policymakers to farmers and other end-users, was at the base of our methodological approach. We aimed to bridge the gap between academic research and non-academic actors holding a deeper understanding of the specific dynamics of the real context. Following the seminal work of Grimble and Wellard (1997) on stakeholder theory, by stakeholders we mean "any organization, group or individual with an interest in or influence over" resource use and management in Water-Ecosystem-Food systems, at the local level of the pilot area.

On a more operational level, in the first phase, a systemic analysis of the contexts in which the policies are supposed to drive changes was carried out to select the key domains of interest for the area and define the reference system's boundaries (Duru *et al.*, 2015). Then, Stakeholder Analysis enabled the systematic identification of a large and diverse range of local stakeholders across the different Nexus domains, as well as the assessment and visualization of their interests and powers to investigate potential and inherent collaborations and conflicts. By applying systematic analysis methodologies, we pursued an in-depth understanding of the stakeholders involved in the local Nexus, making explicit the linkages between the different actors and their stakes in resource use and management. The results of the systematic stakeholder analysis were used to recommend and develop stakeholder engagement strategies and also to support the design of communication tools.

To establish connections and facilitate interaction among identified stakeholders, we developed a "virtual arena" for knowledge sharing, the learning and action alliance (LAA). The LAA was used to develop cross-cutting participatory tools based on a combination of scientific and experiential knowledge.

Among the multiple available tools for supporting stakeholder engagement, the Participatory System Dynamic Modelling (PSDM) was selected in view of its proven ability to account for the complex, non-linear interactions among the different elements characterizing Nexus systems, and to facilitate the integration between models/data and stakeholder knowledge (de Vito *et al.*, 2017; Pagano *et al.*, 2019; Zomorodian *et al.*, 2018). As a robust approach to exploratory analysis of complex systems, the use of PSDM allows the integration of multiple forms of knowledge and data to identify the most suitable Nexus management options to increase resilience in the local context (Sušnik *et al.*, 2018).

In the final phase, which is beyond the scope of this work, an integrated analysis of Nexus ecosystem services will provide the methodological and practical groundwork for the elaboration of harmonised sectoral policies linked to sustainable development goals (Carmona-Moreno *et al.*, 2018), and the design of alternative strategies for resource management solutions to be implemented in the pilot area. The results will provide an evidence-based "solution selection framework" to decision makers, designed to support the selection of alternatives in addressing Water-Ecosystem-Food Nexus challenges, the ultimate goal being the development of a transition roadmap toward integrated, sustainable management of agri-environmental resources.

Study case: the pilot area of Tarquinia (IT)

The pilot area "Tarquinia Plain", is located in Central Italy, Lazio Region around 90 km north of Rome, under a typical Mediterranean climate (Figure 1). The hydrogeological Risk Master Plan (*Piano di assetto idrogeologico*, PAI) of the province has identified the largest flood risk areas in the province, with about 9% of the landscape (25.403 Km^2) classified as being at a high risk of flooding. This major hazard that has already occurred in the past, may in the future cause soil erosion and damage to local infrastructure, leading to negative impacts on agricultural lands and crops (Regione Lazio, 2015; Trigila *et al.*, 2021). The city of Tarquinia, together with nearby Montalto di Castro, has the highest per capita income in the province of Viterbo, the main economic sectors being tourism and agriculture. In fact, in this area 65.87% of total employment is related to tourism, mainly due to the presence of an important Etruscan archaeological site (Tarquinia has been on the World Heritage List UNESCO since 2004), combined with seaside tourism. In the province of Viterbo, Tarquinia is the second municipality in the province with the largest utilized agricultural area (UAA), which accounts for 9.37%

of the total, and hosts 5.37% of the total farms. The most common crops are cereals, horticulture and forage, as shown in Table 1 (data provided by the (data not published, provided by the Water User Association in 2017). Sixty-seven percent of the territory is used for agriculture, and 85% is designated as being nitrate vulnerable zones. Around 45% of the agricultural land is irrigable and, as of 2017, 2195ha were actually irrigated.

Historically, as in most rural areas of Italy, the advent of land reform (1950s) changed the structure of land ownership, which went from large properties to relatively small, family-run farms, ranging in size from 2 to 20 ha. With the development of industry, many farms were abandoned by their original owners who moved to the industrial centers, leading those who remained in the agriculture sector to merge neighboring farms. Later on, the construction of major irrigation infrastructures enabled the transition from extensive agriculture (based on cereals and pasture) to more diversified farming systems, involving the introduction of high-value crops, such as orchards and horticultural crops. In recent years, the amount of farms has decreased significantly, which has been accompanied by a much less marked reduction in the extent of the UAA (farm enlargement). Nonetheless, farms are still fragmented throughout the territory, which makes it difficult to organise and implement structural and technological modernisation measures.

Farming practices are mainly influenced by market dynamics and the common agricultural policy (CAP), the last implemented through both direct payments and rural development plans, as well

Figure 1. Tarquinia plain in central Italy.

Table 1. Major crops, farming systems and water demand of crops in the water user association area in Tarquinia (data provided by the Water User Associations, 2017).

	Crop within Pilot Area	Total area (ha)	Month of sowing/harvest (months of irrigation if applicable)	Average yield (kg/ha) irrigation volume (m^3/ha)	Average
Largest area	Durum Wheat	7800	November-June	4600-5600	Rainfed
2nd largest	Industrial tomatoes	960	May-August	45,000-50,000	3,200
3rd largest	Watermelon	333	May-August	NA	2,500
4th largest	Melon	272	May-August	TBC	2,780
5th largest	Fennel	144	August- January	TBC	940

as the nitrates directive. The governance structure for energy, environment and climate is defined within the framework of the National Energy and Climate Plan. For the water sector, River Basin management plans are the programming and implementation tool for the objectives set out in the Water Framework Directive. Regarding water resources and demand by different sectors, surface water from two rivers (Marta and Mignone) is the main water source for both domestic (47% of total water consumption) and irrigation purposes (53%). In agriculture, the majority of irrigation systems use drip irrigation (63%), the rest use sprinkler systems. The Water Users Association (WUA) "Consorzio di Bonifica Litorale Nord" manages irrigation water in the agricultural area of the Tarquinia plain. In the Tarquinia plain, in 2017 the WUA managed an area of almost 10.000ha as irrigable areas, and more than 2.000ha were irrigated mainly with micro-irrigation systems. The activities of the WUA, while maintaining the original functions of reclamation and irrigation, have gradually expanded to include activities aimed at protecting the soil and mitigating hydrogeological risks. In addition, the WUA ensures the rational use of water for irrigation with management measures and the maintenance of the hydrographic network. According to the hydrogeological Risk Master Plan (PAI) of the Viterbo province, Tarquinia has the largest flood risk areas, with about 9% of the landscape (25.403 Km^2) classified as being at high risk (Figure 2).

The main known local sectoral challenges are water scarcity and poor quality: the quality of groundwater is not very good due to pollution by nitrates from fertilizers. In summer, as a consequence of intense tourism activities, the demand for water increases, which leads to competition between tourist and agricultural use. In light of the above-mentioned issues, one of the main sectoral objectives for Tarquinia is to improve water quality by reducing the amount of Nitrogen fertilizers applied in agriculture by 2027, as foreseen under the Regional Water Protection Plan (*Piano Di Tutela Delle Acque Regionale* - PTAR).

A number of sites of environmental interest can be found in Tarquinia, making it a biodiversity hotspot (Table 2). The "Salt marshes of Tarquinia" Natural Park, about 170 hectares wide, extends along the coast of Tarquinia and consists of a former salt pan of great environmental value due to the presence of rare species of avifauna such as the pink flamingo and the little egret, as well as halophytic flora. Because of its biodiversity, the area has been designated as a site of community importance and a special protection area, making it part of the EU's "Natura 2000" network.

The area is impacted by the nearby thermoelectric plant "ENEL Torrevaldaliga Nord" (total installed power of 1980 MW on three coal-fired units), which ranks second in Italy in terms of CO_2 emissions (around 11 million tonnes per year). This plant is expected to be decarbonized by replacing the coal combustion units with a new gas unit, to accomplish the integrated National Plan for Energy and Climate established in 2019, which foresees

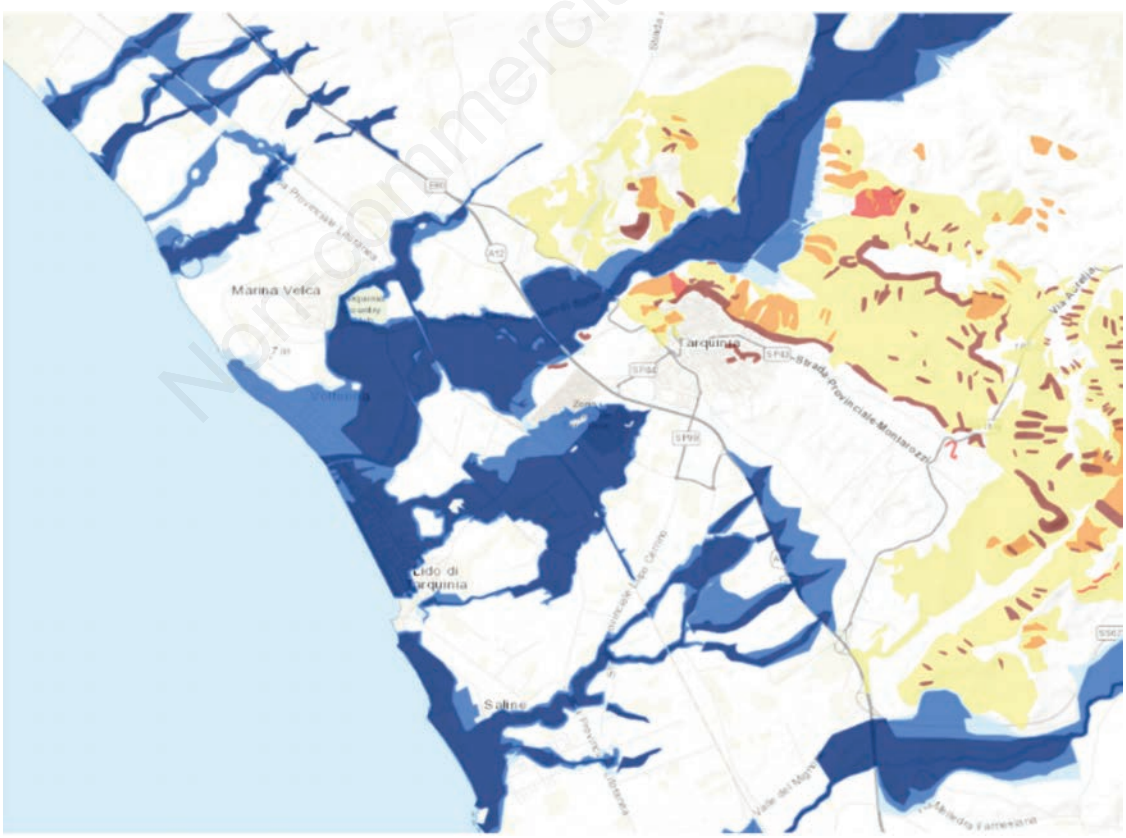

Figure 2. Flooding areas in Tarquinia: dark blue = high probability hazard with 20-/50-year flood return periods; blue = medium probability hazard with 100/200-year flood return periods; light blue = low probability hazard with >200-year flood return periods. From Trigila *et al.* 2021, modified.

the total decarbonization of existing plants by 2025 (goal: 40% reduction in national carbon dioxide emissions by 2030). Several environmental monitoring studies (BIOENEL national project funded by ENEL) have been conducted over the years to assess the impact of thermoelectric plant emissions on the quality of agroecosystems and agricultural production (fallout of heavy metals and pollutants). The results were discussed over time with the municipalities of Tarquinia and Civitavecchia and partially made public through press conferences.

In the area, there have been attempts to involve farmers (and a few others) as key stakeholders in some sectoral research projects. In the context of the H2020 FATIMA project, Blasch *et al*. (2020) investigated farmers' willingness to adopt precision farming technologies. Based on a choice experiment, the authors examined the role of social influence in developing beliefs about precision farming, showing that farmers who have already adopted a new technology can have a positive impact on its broad acceptance within a territory, through knowledge sharing among peers.

Stakeholder Analysis and engagement

Stakeholder Analysis is a systematic tool with well-defined applications and methods for understanding a system and its potential dynamics by "identifying the key actors or stakeholders and assessing their respective interests in the system" (Brugha and Varvasovszky, 2000; Grimble and Wellard, 1997). Through this analytical approach, stakeholders' interests, influences, and roles can be systematically assessed and compared across political, social, and economic sectors from international to local levels, and their relationships can be explored (Grimble *et al.*, 1994; Reed *et al.*, 2009).

Approaches to stakeholder analysis have changed over a long period of time, during which these tools have adapted and evolved in various fields and academic disciplines, becoming increasingly popular in policy and governmental entities, NGOs, businesses, and recent years have seen stakeholder analysis become a core component of natural resource management (Friedman and Miles, 2006; Raum, 2018; Reed *et al.*, 2009; Wezel *et al.*, 2018). In the policy realm, stakeholder research is used mainly to assess the 'relevant actors' and their influence on decision-making processes, facilitating the transparent implementation of policy options. In the fields of natural resource management and agriculture, stakeholder analysis has increasingly been seen as an approach to potentially understand conflicting interests and allow marginal stakeholders to influence decision-making processes, focusing on inclusivity (Di Bene *et al.*, 2019; Duru *et al.*, 2015; Neef and Neubert, 2011; Trinchera *et al.*, 2020; Vanino *et al.*, 2023). Without stakeholder analysis, the lack of understanding of power dynamics can lead to the "usual suspects" of well-connected stakeholders influencing decision-making outcomes more than marginalized, "hard to reach" groups (Barraclough *et al.*, 2022; Ciaccia *et al.*, 2021; Friedman and Miles, 2006; Hurley *et al.*, 2022; Reed *et al.*, and references therein, 2009). For this study, a stakeholder analysis was used to identify stakeholders to be involved in the LAA, applying systematic methods for: i) identifying stakeholders, by means of snowball sampling and semi-structured interviews; ii) differentiating between and categorizing stakeholders, by means of analytical top-down categorization (Figure 3) (Friedman and Miles, 2006; Grimble *et al.*, 1994; Grimble and Wellard, 1997).

An initial assessment was carried out to select key domains of interest for the area and system boundaries (see the study case paragraph) to identify stakeholders at the intersection between farming practices and the WEF Nexus (Duru *et al.*, 2015). Key actors were initially sampled purposefully across the identified domains, adopting an exploratory qualitative approach (Raum, 2018; Savin-Baden and Howell-Major, 2013) to identify a cross-section of stakeholders with a stake in the use and management of natural resources at different levels. Then, snowball sampling interviews were used to extend the coverage: additional stakeholders were identified by interviewing the initial sample, and integrated into the LAA. Snowball sampling was first defined in social science as "a technique for finding research subjects in which one subject gives the researcher the name of another subject, who in turn provides the name of a third, and so on" (Vogt, 1999), and is widely recognized as a structured purposive sampling technique which also allows for flexibility (Bryman, 2012). We decided to conduct informal individual interviews to encourage participants to give open answers and to prevent conflicts among stakeholder groups. This first round of interviews, which preceded further semi-structured interviews described later on, included questions to elicit participants' views on local actors who might

Table 2. Sites of environmental interest in the territory of Tarquinia.

Name	Classification	Total area (ha)	Other
Natural reserve "Salina di Tarquinia" (Salt marshes)	SIC, ZPS	170	
Mignone river (basso corso)	ZPS		Environmental and local associations recently challenged and won against the Orte-Civitavecchia motorway plan which was supposed to cross the Mignone protected area (Oct 2021 and Dec 2022).
Litorale tra Tarquinia e Montalto di Castro	SIC		
Acropoli di Tarquinia	SIC		
Necropoli di Tarquinia	SIC		
Comprensorio Tolfetano-Cerite- Manziate	SIC		
Fondali tra marina di Tarquinia e Punta della Quaglia	SIC		
Fondali tra le foci del Torrente Arrone e del Fiume Marta	SIC		
Tarquinia Gebelletta Monterozzi	WPZ		Water protection zone for human consumption
Tarquinia Pozzi Nardi – Marina Velca – Pozzi Mainardi	WPZ		Water protection zone for human consumption

SIC, site of community importance; WPZ, wetland protection zone; ZPS, special protection zone.

play a crucial role in the Nexus assessment, their influence and interest. The 30-50 min-long interviews were conducted either in person or by telephone between September and November 2021. We assembled a cross-section of stakeholders of all relevant categories, from different organizational types, including a number of public entities at various levels, policymakers, the private sector, farmers, NGOs, *etc*., as well as actors involved in agricultural teaching, advising, and research.

After identifying stakeholders, an analytical categorization into groups was performed to reveal potential conflicts among them. According to Duggan *et al*. (2013), clustering stakeholders into functional groups, *e.g.*, according to their roles, interests and power, provide the fundamental basis for designing multi-user communication interfaces. We defined categories according to each stakeholder's main area of interest in relation to the WEF nexus (the three sectors of water, environment, and food), the type of stakeholders (*i.e.*, policymakers, farmers, and association, citizens, NGOs, individual expert, private companies, academia) and the level of their interest and influence. The stakeholder categories were then combined with an interest-influence matrix to differentiate between those who make management decisions and those who are affected by them, in which way and to what extent (Grimble and Wellard, 1997; Reed *et al*., 2009). For the top-down qualitative assessment of influence and interest, we evaluated how each stakeholder is connected to different challenges in different areas of the nexus, *e.g.*, as a causal agent, as a solution advocate, as an interested party, as an actor with management ability, *etc*. "Influence" is defined here as the ability/power to affect, either positively or negatively, directly or indirectly, any adaptive changes in land and resource management to address the local, core challenges of the Nexus. I "Interest" simply refers to the extent to which these challenges are important to the actor, *i.e.*, is it in his interest to solve them, and is there an important issue for him and/or his business? Scores for level of interest and influence were then calculated on an 11-point-bipolar rating scale, by assigning a value scale from very low to very high to the parameter "interest", and a value scale from very negative impact (stonewalling) to very positive to the parameter "influence", scores were then averaged by stakeholder category (full details in Reed, 2009). Finally, we applied the interest-influence matrix approach to the cross-sectional pool of categorized stakeholders by plotting in a scatter diagram our full range of stakeholders along the gradients of their "interest in" and "influence on". We intended to uncover and understand the full web of relationships between them, as well as potential conflicts and contestations in trade-offs and management decisions (Howe *et al.*, 2014), and prioritize and tailor the engagement efforts. Systematically mapping stakeholders to better understand their multiple stakes, has been found to strongly help in developing governance and management strategies when dealing with natural resource use and sustainable agricultural practices (Raum, 2018).

The Learning and Action Alliance

The term "Learning and Action Alliance" comes from the work of Butterworth *et al.* (2008) who defined learning alliances as "a group of individuals or organizations with a shared interest in innovation and the scaling-up of innovation in a topic of mutual interest". Newman *et al*. (2011) added the word "Action" to emphasize the importance of LAAs in delivering innovative solutions identified by their members through co-learning processes. In this study, the LAA environment was the virtual space for stakeholder engagement where mutual learning and cross-fertilization were promoted by integrating different types of knowledge and provid-

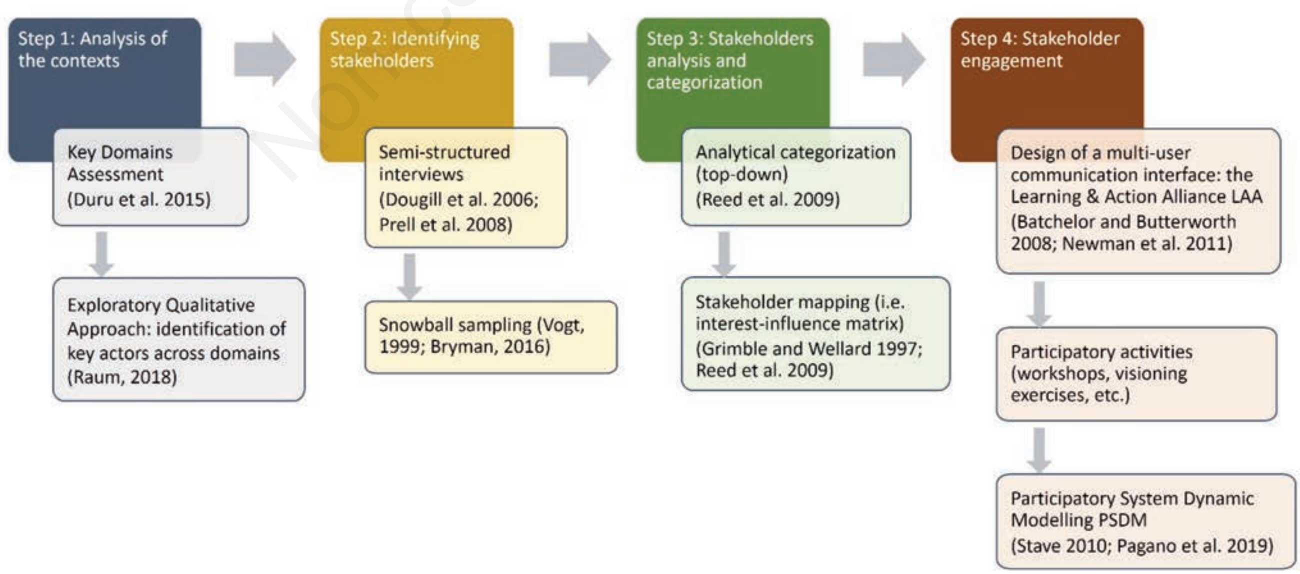

Figure 3. Methodological framework for stakeholder analysis and engagement (rationale) and methodologies used for: i) identifying stakeholders (Steps 1 and 2); ii) categorizing stakeholders and investigating their behaviors and relationships (Steps 3 and 4). From Reed et al. (2009), modified.

ing one voice for all stakeholders, thereby limiting power asymmetries. The LAA was the social structure that supported the implementation of multi-domain participatory tools for the co-creation of knowledge, *e.g.*, through physical engagement in different activities such as workshops, trainings, webinars, *etc*.

As described by Brugnach and Ingram (2012), knowledge co-production differs substantially from academic knowledge production approaches (Table 3). In contemporary academic knowledge production, outputs can be bodies of abstract statements, problems can be solved by processing information, solutions are produced apart from problems and situations, and only accepting one valid frame. The objective of LAA's co-production of knowledge is to tackle this issue through relational practices. The activity of the LAA can be seen as a social learning system where several individuals representing different domains of knowledge engage in common activities, share information, develop skills and build solutions together, making them members of a community (Wenger, 2010). The process of interrelations and knowledge exchange allows them to learn together, and to understand the position and concerns of each member, turning conflict and divergence of interest into collaboration. In the LAA environment, a structured visioning process helps drive the Nexus dialogue: each stage of the engagement process is visualized through sketches, mind maps, videos, interviews, etc. to bridge the gap among divergent interests and converge toward common goals. Visualization is one of the most important engagement tools: it aids in the creation of a vision towards which decision-makers can converge as they discuss how to face systemic Nexus challenges, or from which they can take a step back to examine proposed solutions and provide feedback in an iterative process.

The LAA was the forum for applying a deep transformative participatory approach by: i) meetings and semi-structured interviews; ii) a workshop that involved the participation of all stakeholders; iii) visioning exercises, aimed at co-developing desirable visions and pathways for Nexus management in the given pilot, largely based on the work of Shinko *et al*. (2022) and Magnuszewski *et al*. (2020); iv) the learning platform "LENSES Window", a web-based learning platform based on the education software Moodle, which aimed to serve as a "one-stop-shop" for all information, resources and digital engagement tools for the pilot area.

Participatory System Dynamic Modelling

PSDM for collaborative learning was introduced in the LAA environment with the aim to: i) co-define system characteristics and dynamics, ultimately improving its understanding; ii) build and analyze scenarios with stakeholders, to select suitable strategies at multiple scales. Thus, stakeholders were actively involved in knowledge elicitation as well as the modeling phases, facilitating the integration of different forms of knowledge to co-define characteristics and dynamics of the WEF Nexus in the local context. In the following, a summary of the key steps of the methodology is reported.

The proposed framework for PSDM implementation comprises multiple steps, and is based on the integration of a series of participatory and desk-based activities. It describes a highly iterative process, as it involves constant iterations with pilot areas. The framework basically comprises two major modeling phases. The first one is broadly defined as 'qualitative', and oriented to provide an improved understanding of the 'Nexus structure' based on the definition of a Causal Loop Diagram (CLD). CLDs (full details in Sterman, 2000) provide a straightforward graphical representation of the system, focusing on the relationships among different variables, and characterizing the strength of such relationships. The direction of the connections between such variables defines the causal dependency, being positive (+) if the variables change in the same direction or negative (−) if they change in the opposite direction. Combinations of positive and negative causal relationships can form either reinforcing ('R'), and balancing ('B') feedback loops, which are crucial to describe the expected dynamic evolution of variables. The second step is defined as 'quantitative' and oriented to produce stock and flow models. Both qualitative and quantitative models can be then used to perform scenario analysis. The present work focuses on the first phase only, which has been recently concluded in the Tarquinia area based on the following activities:

Baseline analysis of the pilot area, performed through a review of existing documents and background information provided by the initial assessment of the key domains of interest and system boundaries, aiming at providing a basic understanding of the pilot area and of the main Nexus challenges and strategic objectives. Particular attention is given to the analysis of the key policies (both implemented and planned) and the evidence from previous projects and activities. During this step, a preliminary CLD is built.

Interviews. A round of semi-structured interviews was conducted with stakeholders, referring to the sector (or domain) the interviewee was mostly related to. Basically, the rationale of the interviews was to identify critical connections between the sectoral security level, and the level of satisfaction of the main needs expressed by the stakeholders, identifying all the most influential processes (both natural and anthropic), barriers and drivers. The analysis was mainly focused on the current system state ('Business-as-usual'), but also providing information on the expected system evolution under current major drivers (*e.g.*, climate change, economic conditions, *etc.*). As a result, the CLD was revised considering the information provided by the stakeholders. Due to the SARS-CoV-2 pandemic, we conducted some interviews using the TEAMS video conference software, and others in the presence of the participants following required social distance procedures.

Workshop. During the workshop that was organized in the LAA of the pilot area, a validation of some key connections of the

Table 3. Core principles of the engagement process in the Learning and Action Alliance environment.

Co-production	Builds upon the integration of the many types of knowledge that stakeholders and project partners bring to the table, including technical and practical knowledge, to frame a wide and inclusive picture of existing challenges (Brugnach and Ingram, 2012).
Cross-fertilization	Exchange of knowledge to favour mutual learning between different actors. This knowledge exchange might include technical and practical experiences (*e.g*., good and bad practices) and supports the co-creation process.
Capacity building	Capacity building activities are foreseen to lift technical and institutional capacities for Nexus management (*e.g*., simulation games, dedicated webinars, 'train the trainers' exercises, *etc)*.

CLD was performed, seeking to find an agreement on the key challenges for the area. This activity was performed considering two different tasks: i) a participatory mapping exercise was performed to geographically locate the main elements/variables of the model; ii) key cause-effect connections among the variables were drawn on a blank map, while being discussed by the stakeholders. The information obtained in step ii) were useful to update/revise the CLD, while the information obtained in step i) will be useful for the future development of the quantitative model.

Within the framework of PSDM, further future interactions with stakeholders are foreseen, mainly oriented towards the validation and use of the PSDM for co-design and co-evaluation of scenarios.

Results and Discussion

In this study, a stakeholder analysis was used as a functional tool to promote a multi-level stakeholder involvement in Nexus assessment. We identified a group of experts and institutional actors (n=9) as influential and closely involved in the dynamics of the identified local domains. This group included representatives from public (n=3), private (n=4), and non-profit sectors (n=2), who provided us with information on a variety of organizations, individuals and associations that were deemed critical to the Nexus assessment, and which were required to be included in the evaluation process to reflect a wider range of societal needs and preferences. Then we broadened the audience of relevant stakeholders in an iterative processes, by means of a snowball sampling methodology and top-down analytical categorization: we identified n=21 stakeholder functional clusters based on their roles and main interests in the Nexus different sectors (F=Food, W=Water, E=Environment), and n=6 categories based on the type of stakeholder: policymakers [POL]; farmers and associations [USER]; citizens and NGOs [CIT]; individual experts [EXP]; private companies [COM]; academia [RES] (n=5 categories for water and environment, n=11 categories for food) (Figure 4). We assembled a full cross-sectoral range of stakeholders (n=41) from different types of organizations: public entities and policymakers at different levels (n. 9); farmers and associations (n. 11); farming companies (n. 9), of which n. 3 are involved also in the tourism sector through "farm tourism" activities; private sector (n=1); NGOs and local associations (n. 3); actors involved in agricultural teaching, advising, and research (n = 10) (Figure 4). In the case of the present analysis, the diversity of stakeholders successfully

Figure 4. Full cross-sectional range of stakeholders (n=41) and levels of interest and influence. Functional clusters: F=food, W=water, E=environment; functional categories: policymakers [POL], farmers and associations [USER], citizens and NGOs [CIT], individual experts [EXP], private companies [COM], academia [RES]. Scores for level of interest and influence were calculated on a 11-point bipolar rating scale, stakeholder names have been coded [XYZ] in compliant with general data protection regulation (EU) 2016/679.

involved reflects the different water-ecosystem-food environments and representatives, as well as the large proportion of beneficiaries who may be affected by changes in land resources management. Results confirmed the ability of the snowball sampling methodology in identifying all relevant stakeholders, especially when dealing with diverse communities from which hard-to-reach subgroups are to be included (see *e.g.*, Atkinson and Flint, 2001). Snowball sampling allowed us to gradually involve relevant stakeholders in the process and, relying also on personal trust and on the existing network of contacts, significantly increased the willingness to participate. As a result, the "cold calls" tended toward zero. Common engagement methods may fail to involve hard-to-reach stakeholders (Chilvers and Kearnes, 2016; Ciaccia *et al.*, 2021; Hurley *et al.*, 2022), thus potentially leading to information asymmetries and inaccurate representation of the Nexus and its challenges. Therefore, different types of activities were organized for specifically targeting stakeholders, *i.e.*, individual interviews, focus groups, short meetings and expert consultations. One of the most positive outcomes was the active involvement of multiple stakeholder classes, including farmers with low digital literacy, such as older farmers, who were more vulnerable to the digital divide. In this case, the role of the word of mouth (as seen in Blasch *et al.*, 2020) was crucial. We also found that previous engagement experiences may affect the willingness of some actors to be involved again in the process. Some of the farmers we included in this study, for example, were at first reluctant to participate, stating they had previous experiences with researchers and/or policymakers, which they subjectively perceived had led to little or no practical outcomes, affecting their confidence in the participation process and their sense of ownership. As the final phase of the stakeholder analysis, we plotted stakeholders in an interest-influence matrix (Figure 5). Based on the position on the map, specific behavioral characteristics and attitudes can be associated with stakeholders. Generally, stakeholders' attitudes are based on judgments based on social learning and personal experiences, and their behavior reflects these preferences and dispositions when expressed. In Figure 5, in the upper right corner of the win-win square, we identified a group of influential, priority stakeholders, all having a high stake and a high interest, which had to be closely and fully engaged. Most of them are public management bodies belonging to the water sector of the Nexus, and, interestingly, all of them appear to be currently involved, together with universities and several local authorities and associations, in a territorial planning agreement called CO.LA. FI.CO. (River, Lake, Coastal and Landscape Agreement), which aims to negotiate the environmental restoration of the hydrographic basins of Lake Bolsena, the River Marta, and the coast of Tarquinia.

Most of the stakeholders identified as relevant to the "Food" sector (*e.g.*, individual farmers, associations, decision-makers, and researchers) and in the "Environment" sector of the Nexus (*e.g.*, NGOs and local environmental associations), were found to have moderate or low influence but high interest, which is usually a characteristic of project 'supporters' (or 'keepers'). Accordingly, they were regarded as primary stakeholders in the project and have been always kept in the loop as they can help achieve positive and long-lasting outcomes. Interestingly, the position of agricultural experts and consultants (F7) in the matrix highlights the pivotal role they can play in adopting innovation in land and resource management and, in this case, in changing farming practices to achieve sustainability. A different attitude of farmers and farming

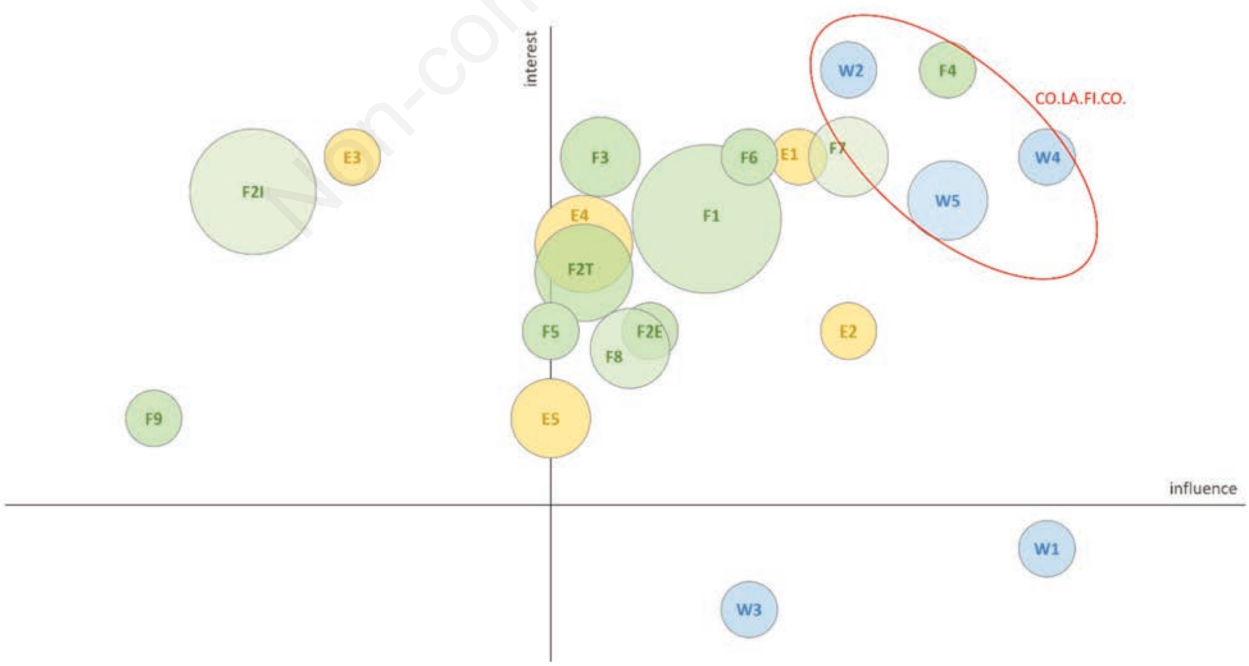

Figure 5. Stakeholder Mapping: bubble chart showing the positioning of functional clusters based on the discrete distribution of stakeholder interests and influence, the size of bubbles indicates the groups size.

companies towards potential systemic changes can be observed depending on the level of production intensification: farmers practising intensive farming (F2I) show on average an impeding attitude towards possible changes to the *status quo*, which is probably due to the amount of capital invested to achieve a competitive position, and the fact that further large investments would be needed to adapt to new management rules. They (F2I) show a higher interest compared to extensive farmers (F2E), as they are more affected by changes in resource and land management, and consequently may themselves have a moderate to low impact on the implementation of policy designs, depending on the strength and extent of their -supposed negative- influence.

It is reasonable to expect a similar behavioral attitude from decision-makers related to tourism (E3, excluding farm tourism), which makes heavy demands on resources, especially water in months of scarcity, and thus competes with other productive activities of the area. On the other hand, companies that supply products and services for agricultural activities (F9) show an interest that is only indirectly expressed and therefore appears moderate, even though they may also be affected by systemic changes in resource use reduction/optimization. The position of the local water users' association (CBLN) is noteworthy, in that it has a great influence on co-developing and implementing resource management policies for agriculture, but appears to be rather inert when it comes to holding a stake in the process (W1). Most likely, this may be due to the multiple political and financial entanglements of its administrative processes, making it somewhat slow to identify and respond to local specific needs and conditions.

As a whole, clustering and mapping of stakeholders into functional roles served as fundamental knowledge by clearly depicting who makes decisions, who is affected by them, in what way and to what extent, which is a novel aspect of our findings. It is worth mentioning that the functional categorization performed on stakeholders, and the analytical assessment of their influence and interest, even if updated on feedbacks from interviews (which included questions about participants' views on stakeholders' influence and interest), are generally a result of a simplification which tends to ignore behavioral changes, or differences between attitudes and behaviors (see *e.g.*, Burton, 2006; Hurley *et al.*, 2022). Nonetheless, these systematic tools provided a structured approach to get a "snapshot" of otherwise elusive stakeholder dynamics, helping to describe the complex network of power/interest interactions in a given time and space, upon which we were able to tailor engagement strategies and design communication tools. Based on the results from stakeholder analysis and mapping, which enabled us to identify key needs and requirements at pilot scale, participatory activities to be implemented in the LAA environment were also tailored. As already mentioned, not all the stakeholder groups were involved at the same time and using the same approach, as mismanagement of power dynamics could have hindered the success of the engagement process and limit the recognition of the value and contribution of each actor. These activities were also structured to guarantee a gradual broadening of perspective, and thus followed an iterative sequence from individual interviews through focus groups to a global workshop. The structure of participatory activities also allowed stakeholders to gradually move towards consensus in the visions for addressing Nexus trade-offs. This was particularly important in our study in the Tarquinia area, as some of the stakeholders indicated a high level of conflict and a limited interest in being involved in joint activities. In this direction, starting from individual interviews helped address real or perceived power disparities among participants and encouraged them to be frank in their responses, without the issues that may characterize group dynamics. Furthermore, we promoted transparency and consistency by asking all interviewees the same set of questions, while also allowing for researcher discretion in prompting and following up with the interviewee on points of interest. In particular, some questions were modified depending on the technical background of the interviewee, and some space was left both for the interviewee to focus on highly relevant topics and for the interviewer to be able to follow up in case clarifications were needed.

The LAA was thus employed as the local forum for transforming conflicts and divergence of interests into collaboration by applying a deep, transformative participatory approach to expose and discuss key local issues, visions, conflicts, gaps and needs with the aim of setting the basis for social and institutional cross-sectoral agreements on integrated and sustainable Nexus management. Among all involved stakeholders, only one participant declined to participate in joint activities, preferring to be interviewed separately by the researchers.

As mentioned before, the wide range of participatory activities that have been conducted (so far) in the LAA, involving increasingly large groups of participants from individual interviews to collective visioning exercises, increased the capacity of its members to deal with different perspectives and behaviors (core princi-

Figure 6. Some examples of the set of cards describing infrastructures, economic activities and resources of the local Water-Ecosystem-Food Nexus, for participatory geographical mapping during visioning exercises.

ple: capacity building) and to reshape knowledge through co-production and cross-fertilization, as reported for PSDM (Table 3). The LAA proved to be an effective tool for fostering engagement and collaboration, probably because in the LAA environment an iterative process of social learning was activated through community interaction (O'Donnel *et al.*, 2018): there was evidence of short-term changes at both the individual level, *e.g.*, changes in individual attitudes (awareness and acquisition of new knowledge), and collective level, *e.g.*, joint understanding and discussion of Nexus challenges and agreement on potential actions.

On the opposite side, it should be remarked that among the participatory activities implemented into the LAA, the digital learning platform "LENSES Window" (http://www.lenseswindow.eu) achieved the lowest results in terms of content implementation and website overall traffic. The purpose of the platform, indented as digital engagement tools, was to serve as a "one-stop-shop" for all information, resources and activities of the pilot, mirroring and extending digitally the community built in the LAA environment. Even though the platform had customized features (*e.g.*, a repository, calendar and news sections, a forum for sharing success stories, etc.), could have multiple users and was made accessible to both researchers and stakeholders, it never really got off the ground. Likely, this was because we had not properly considered the time and expertise that this kind of activities would require, so that they could have been better incorporated into a more structured task with local, dedicated professional staff, or integrated into institutional digital platforms already active locally (*e.g.*, well-known territorial information websites). Moreover, the learning platform could have greatly benefited from synchronization/interaction with social media, *e.g.*, by opening social media accounts dedicated to Tarquinia participatory activities, which have a much wider reach and are more effective in disseminating information quickly and in an easily accessible way, *e.g.*, by phone from wherever the stakeholders are (Toukola and Ahola, 2022; Baratella and Berggreen, in prep.). It should be added that, in line with O'Donnel *et al*. (2018), the limited success of the digital platform "LENSES Window" may suggest that face-to-face interaction between members remains the most effective way for social learning to negotiate and develop a shared vision. In fact, LAA activities resulted in the most suitable, integrated approach for overcoming "silo thinking" among stakeholders and the most effective to develop shared visions and pathways to pilot-scale innovations. The opportunity to manage a multi-functional arena in which to plan several kinds of activities to discuss common interests strongly helped the removal of barriers to information sharing and fostered a mutual sense of trust and ownership among participants, both stakeholders and researchers. Among participatory activities, the visioning exercises and PSDM were clustered within a workshop held to involve the majority of stakeholders. The visioning exercises were the key par-

Figure 7. Participatory geographical mapping for the Tarquinia pilot: identification and location of the main elements/variables that characterize the area.

Figure 8. Participatory conceptual modelling for the Tarquinia pilot: interconnections and interdependencies among main elements/variables that characterize the area and weighted cause-effect relationships.

ticipatory activity implemented during the workshop with the aim to co-develop desirable future visions and pathways for the water, environment and food systems, and to identify the actions needed to realise these visions in the given pilot area (Magnuszewski *et al.*, 2020; Shinko *et al.*, 2022). The first step of the visioning process was to visually represent the current situation of the local WEF Nexus with the stakeholders, in a simplified visual format. For this purpose, a large printed map of the Tarquinia pilot area and a set of cards describing infrastructures, economic activities and resources was used (Figure 6). The cards were provided to stakeholders during discussions, and placed on the map by them to facilitate visual representation and better understanding of the system challenges, as well as to reveal the main issues faced by stakeholders within and between sectors (Figure 7). With the help of the maps, stakeholders identified and located the most important elements/variables of the Tarquinia area (participatory mapping exercise), then they drew and characterised the main interconnections and interdependencies between those elements, identifying chains of cause-effect relationships and weighting connections (Figure 8). The various socio-economic activities, human and natural resources, pressures, drivers and impacts comprising the sets of pathways that are required to achieve the different visions were collectively explored in their potential trade-offs and synergies. Stakeholders' values and preferences shaped different visions for the desired future and ways to achieve it, and these divergent viewpoints manifested themselves in the need to weigh difficult trade-offs. An overview of the main variables and of their cause-effect connections that can be used for describing the Nexus in the study area was then provided to stakeholders by the CLD developed within the PSDM framework (Figure 9). It included both the information available in the baseline description of the pilot area and the stakeholders' knowledge elicited through interviews (mainly performed in the period December 2021 – January 2022) and feedback obtained from the workshop. The CLD (Figure 9) depicts both general variables and variables related to the biophysical realm as well as the socio-institutional dimension. The CLD highlights the key Ecosystem Services (in green), as well as the main existing pressures (in red) due to both external drivers - *e.g.*, climate change impacts - and internal processes - *e.g.*, intensive use of chemicals and fertilizers in agriculture and the tendency to intensify agriculture as it is associated with higher profitability. Moreover, the cause-effect relationships between variables are defined by their direction and polarity, which highlight their dependence.

The development of the CLD was useful to structure the Nexus dialogue, through the identification of the main challenges for the pilot area and a deeper understanding of the multiple interconnections and interdependencies around them. Two central challenges were identified: i) the need to develop 'sustainable' agriculture (that is, profitable but also capable of preserving ecosystems); ii) the protection of the system lake-river-coast and ecosystem conservation (for landscape value).

The structure of the CLD reflects the baseline knowledge and the stakeholder knowledge around those challenges. Specifically, the first piece of information that emerged during participatory activities was that Tarquinia's agricultural producers have long sought to compete in global markets, from which they are often excluded due to their small size compared to the large companies in the sector: in fact, farms are still fragmented throughout the territory, which makes it difficult to organize and implement structural and technological modernization measures. In this regard, the CLD shows that variables such as 'Favorable market conditions' and 'Innovation in agricultural practices' exert an influence (either direct or indirect) on 'Agricultural productivity', thus also affect-

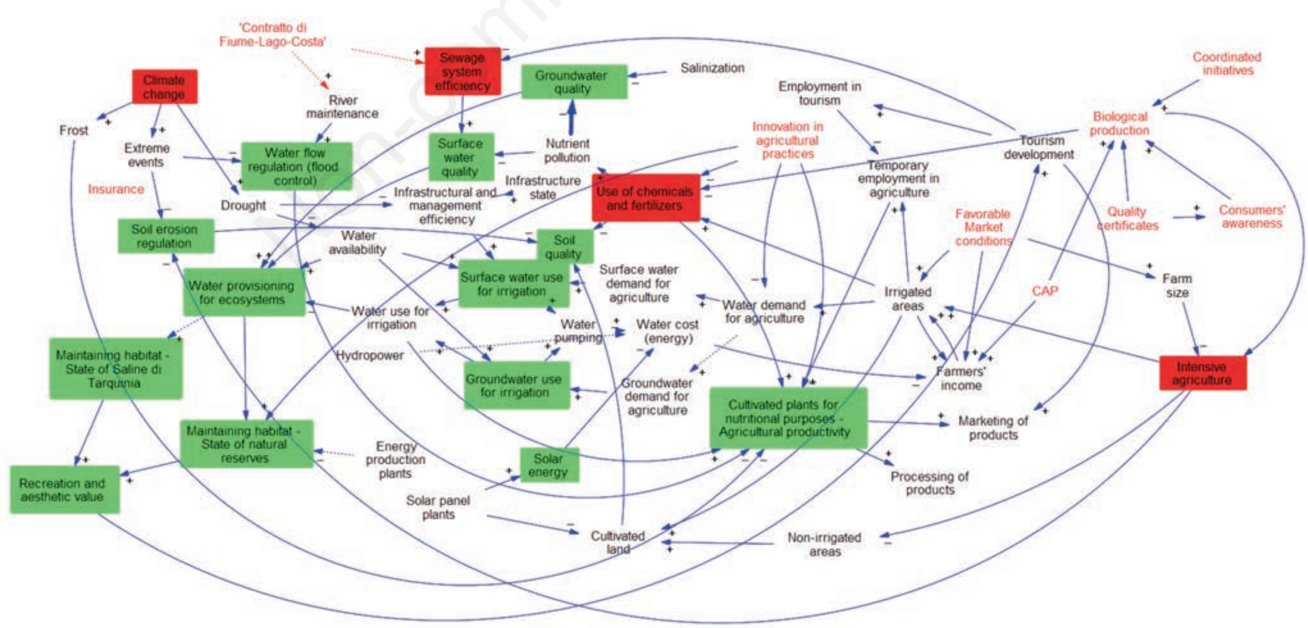

Figure 9. Causal Loop Diagram for the Tarquinia pilot area: general variables are in black, variables referring to the socio-institutional dimension are in red. Green boxes identify variables used for the identification of the most relevant ecosystem services, red boxes represent the existing pressures due to both external drivers -and internal processes. The arrows define the direction of a cause-effect relationship between variables, while the polarity characterizes the dependency: (+) identifies variables that change in the same direction (*i.e.*, they both increase or decrease), while a (-) identifies variables that change in an opposite direction.

ing 'Farmers' income'. This also has impacts, among others, on the water sector and on the water demand for irrigation. The population of farmers is perceived to be quite heterogeneous, with a wide range of old farmers (with limited innovation potential) as well as consortia and groups formed to better deal with market conditions, and efficient enterprises. In contrast to that reported by Blasch *et al*. (2020), we found that farmers in the study area generally seemed to be quite open to the adoption of innovations (*e.g.*, renewable energy systems, precision farming technologies), although they stated specific support may be needed to overcome socio-economic barriers, in particular farm size and the digital divide suffered by older farmers. Indeed, the model shows that the development of 'Coordinated initiatives', 'Innovation in agricultural practices' and economic incentives (such as the 'CAP') can positively contribute to the sustainability and productivity of agriculture, also through support of high-quality local production (including organic).

Seasonal tourism is perceived as having the potential to cause significant fluctuations in the temporary employment sector, primarily to the detriment of agriculture, and to also show other negative impacts (*e.g.*, the increasing load in wastewater treatment plants, which can be an additional point source of pollution for the water bodies). However, 'tourism development' can create a significant increase in sales and consumption of fresh local products in the summer season, to the benefit of small and medium-sized farmers (increasing the potential for 'marketing of products'). In this direction, one of the goals greatly requested by farmers and farming companies was to develop a long-term strategy to improve the quality and marketing of agricultural products, as in the case of the local specialty 'Fennel Tarquinia Protected Geographical Indication. They asked also for a better interaction with the tourism sector by exploiting the multifunctional aspect of agriculture (farm tourism, "food and wine" leisure activities, and the combination of nature, culture and sport in the rural landscape). In this sense, it was pointed out by many, the significant step forward taken with the establishment of the "BioDistretto Maremma Etrusca and Monti della Tolfa", an ecoregion based on the cooperation between the public and private sectors for a new vision of territorial governance. It involves 4 municipalities and its stated goal is to spread organic culture and raise awareness of a model of tourism and territorial development that is both sustainable and compatible with the needs of businesses and local communities.

From an environmental point of view, 'Climate change' is perceived as a relevant driver, and mainly included in the models in terms increasing 'extreme events': the frequency and severity of drought phenomena and periodic flooding, along with 'frost' occurrence can impact agricultural production but also contribute to reduced 'soil quality'. 'Intensive agriculture' itself can also affect 'soil quality', causing soil degradation due to poor (or improper) management contributing to 'soil erosion'. Also due to such conditions, land abandonment has been identified as one of the increasingly relevant problems for land management in Tarquinia. A relevant conflict exists, mainly in the water sector, as there is a significant competition for water use related to irrigation and the need for 'water provisioning for ecosystems', considering also the fragile (and high value) environment that characterizes the area. The distribution of water for irrigation was described by many stakeholders as difficult, due to the structural and administrative problems (*e.g.*, the poor 'infrastructure state') of the

WUA and the high energy costs of pumping water in the irrigation network. The modernisation of the irrigation system, which is managed by the WUA and fed mainly by surface water, is not easy due to political and administrative problems. The system operates on demand and there are no metering systems, so there is no accurate knowledge of water use and illegal water withdrawal/use may occur.

Regarding surface water, several stakeholders report competing water uses related to fluctuating population levels in the summer, and with respect to groundwater, they assess the problem of salinization in coastal areas as generally not very serious. The nitrate issue is well perceived by both farmers and policymakers, who are aware of the regional plan that makes water quality one of the main sectoral objectives for Tarquinia and establishes that water quality must be improved by 2027 by reducing fertilization in agriculture (PTAR*)*. The nitrate issue should also be placed in a broader picture, considering that there are several protected areas and places of community importance that serve as a tourist catalyst which may be affected. Following the workshop, a second phase of PSDM modelling will be performed in the future to build a preliminary version of the stock and flow model for the area, which goes beyond the scope of this paper.

Overall, these findings provide a comprehensive understanding of the needs and challenges faced by local, cross-sectoral stakeholders at multiple scales as a result of implementing a novel methodological framework to reverse "siloed" approaches to agri-environmental resource analysis and management. This innovative methodological approach, added value of this study, is designed to challenge traditional academic settings of capturing stakeholder knowledge by focusing on descriptive and observational approaches (Menconi *et al.*, 2017; Sušnik and Staddon, 2021)*.* Our results show that, when analysing natural resource domains, stakeholder interaction and knowledge sharing can heighten awareness of the Nexus complex interlinkages and of the multifaceted impacts of management innovations for sustainability, at both individual and collective levels. In this sense, our study supports the work of Howarth and Monasterolo (2017) and confirms O'Donnel *et al*. (2018) and Norstrom *et al*. (2020) in their conclusions on social learning activation and knowledge co-production*.* The bottom-up integration of different types of scientific knowledge and practical expertise from across the three WEF sectors, provided the necessary baseline data for addressing Nexus challenges and supporting decision-makers in selecting alternatives. However, the process of co-creating knowledge required a deep understanding of stakeholder roles, needs, and interactions to facilitate the kind of collaboration where stakeholders could raise their voices and freely discuss. We met this widely recognized need of Nexus research (Barraclough *et al.*, 2022; Howarth and Monasterolo, 2017) by applying systematic tools and methods that enabled us to gain deep knowledge of the web of relationships among local stakeholders, their interests, and their potential behaviors within the Nexus.

Conclusions

Multi-stakeholder dialogues, knowledge co-production, and policy co-design are increasingly used globally to achieve the behavioral and organizational changes required for a successful transition towards more sustainable forms of natural resource management and farming practices. The involvement of stakeholders in policy design and decision-making processes can lead to better outcomes by reducing uncertainties and information asymmetries, making it more likely to achieve effectiveness in response to climate change and biodiversity loss, in terms of environmental and economic benefits on multiple scales.

Through the "wisdom of crowds" effect, the expertise of actors operating in practice across the WEF Nexus can generate more accurate knowledge about the system peculiarities than one single layer of experts or decision-makers, whose thinking tends to be similar, so they are less likely to cover a wide range of viewpoints. This is particularly evident in the Nexus assessment, whose conceptual framework aims to disclose the multidimensional interconnections in resource use and production to address environmental sustainability, and thus calls for knowledge co-creation, resolution of conflicts and cooperation. A broad stakeholder engagement to identify WEF linkages and feedbacks plays a crucial role in the success of Nexus projects, allowing for a holistic approach to cross-sectoral dynamics and system complexity. It highlights divergent interests and common goals among stakeholders, stimulates co-creation and mutual validation of knowledge, and legitimizes scientific models. Additionally, participatory approaches serve a normative function by encouraging a sense of ownership among stakeholders, emphasizing the process of inclusion and participation, and enhancing trust through increased transparency. Yet, relatively few studies appear to have specifically engaged stakeholders as active partners in the Nexus framework, and those that have, viewed them merely as end-users.

In this study, we applied stakeholder analysis and participatory approach to gain a detailed understanding of stakeholders' interests and attitudes, which in turn helped to create a shared, deeper understanding of the Nexus challenges. Having a cross-sectoral and interdisciplinary approach, this study promoted meaningful engagement with a wide range of stakeholders at multiple levels, facilitated by the application of an integrated methodological approach that included: i) the systematic stakeholder mapping and analysis, which enabled us to gain in-depth knowledge of all relevant actors and to discover their interactions and likely behaviors; ii) the LAA structure; iii) the PSDM approach. "Siloed" stakeholders were systematically targeted, mapped and actively engaged through mutual learning activities, which helped them to visualize farming practices, land and water management issues, as well as see the impact of innovations, beyond their immediate field of expertise.

A key element of innovation was the integration of stakeholder mapping and analysis with relevant spatial information from participatory mapping exercise. This methodological approach provides a fundamental informative base for spatially explicit scenario analysis in the area, taking into account stakeholder views and local agri-environmental issues. In this framework, the use of CLD helped map and visualize the main interdependencies among variables describing a multiplicity of dynamics, ultimately overcoming the "silo" approach. The impact of using PSDM tools (CLDs) was threefold: i) the CLD allowed integration of different sources of knowledge (scientific and stakeholder knowledge) in a straightforward graphical form, ultimately guaranteeing the development of a 'shared' model for better characterization of a Nexus system; ii) the CLD helped highlight the main dynamics and developing 'narratives' that can be used to better understand the main issues and the potential leverage points for effective policy design; iii) the transition towards a quantitative ''stock and flow' model can help comparatively assess scenarios, and test the different implications of policy actions on the system as a whole.

The whole engagement strategy was based on defining a set of guiding questions, *e.g.*, which we do need to engage and for what purpose (*i.e.*, stakeholder mapping and analysis), how much is required from stakeholders, and what they get in return (participatory engagement tools and PSDM). Our initial assumption was that stakeholders are not merely data providers or local actors receiving a flow of information from the top down, but that the input and interaction of stakeholders from key Nexus sectors was the core of the research. The ongoing dialogue was aimed at better framing the complexity of the Nexus and assessing the potential impact of innovations in farming practices, land and water management in the real context where changes are expected to be implemented. The mutual-learning activities, tapping into actors' deep understanding of specific local dynamics, served to connect contextual insights into the Nexus space for broadening the agreement on potential locally-tailored solutions for sustainable farming practices and integrated management of natural resources, ultimately increasing the relevance and transferability of the research findings.

Common engagement methods have been shown to favor the usual, powerful voices at the expense of all those actors who are less able or less willing to participate actively because of, for example, contrasting perspectives, potentially conflicting interests, lack of motivation or simply because they are not aware of the possibility. Our rationale for the systematic participatory approach was precisely to ensure the engagement of everyone who could potentially hold a stake in WEF Nexus policies: farmers, local authorities, companies, citizens and obviously, nature. Above all, involving farmers in this process is the key, and we paid particular attention to engaging farmers, who are traditionally harder for researchers and institutions to reach. Italian farmers are typically quite fragmented, as in the case of Tarquinia, making it difficult to achieve the "critical mass" needed to engage in addressing complex agricultural challenges and to support policymakers in developing management innovations.

We have learned, in particular, that by actively involving stakeholders from multiple sectors from the very beginning, we were able to acquire, and collectively share, a better understanding of their knowledge, as well as behavior and attitudes, facilitating a move from sector-based to Nexus-wide knowledge. The value of this approach lies in how it impacts both research and policy strategies, thereby closing the gap between them. This approach has an impact on policy as it can help develop a workable strategy for sustainability and define locally tailored mitigation strategies for managing natural resources under climate change. It also has an impact on research, as the development of a methodological framework for stakeholder engagement enabled Nexus researchers to ground the analysis of system state and inter-sectoral challenges in context-specific knowledge and experience. The combination of scientific approaches with stakeholder knowledge led to a deeper understanding of societal challenges and boosted the awareness of intersectoral interconnections, as well as the multidimensional impacts associated with the introduction of innovations in agriculture and land and water management. In a context where the uptake of the Nexus concept in management and practice is still slow, achieving such a broad view served as a "local key" to find entry points and levers for developing management innovation to highlight the impact and benefits that WEF Nexus planning and intervention measures have at different levels.

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