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Combining social network analysis and agent-based model for enabling nature-based solution implementation: The case of Medina del Campo (Spain)

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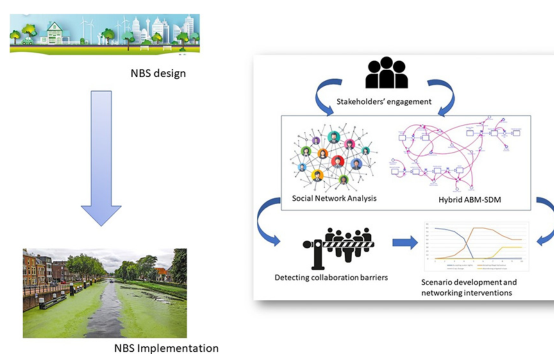
HIGHLIGHTS

- Enabling NBS implementation claims for addressing collaboration barriers
- Lack of effective interactions could lead to conflicts hampering NBS implementation.
- Actions are needed to realign agents' interaction facilitating cooperation.
- Participatory modelling contributed to overcome the collaboration barriers.

GRAPHICAL ABSTRACT



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ABSTRACT

Several barriers still hamper the effective implementation of Nature-Based Solutions (NBS). Among the others, this work focuses on collaboration barriers. NBS implementation claims for effective collaboration among different decision-agents. However, ambiguity in problem framings, which is ineradicable in multi-agents' decision environments, could create collaboration barriers. This work aims to demonstrate that collaboration barriers to NBS implementation can be overcome by enhancing the network of interactions among the decision-agents. An innovative method based on the integration between Social Network Analysis and hybrid Agent-Based Model/System Dynamic Model was adopted to this aim. The analysis results were used for designing networking interventions, i.e. efforts using social network characteristics that could enhance interactions mechanisms among decision-agents. The developed method was implemented in the Medina del Campo (Spain) case study. This area is characterised by one of the most critical groundwater bodies of the Duero River Basin. This work aims at supporting the implementation of suitable NBS to stop the degradation of the groundwater status and associated ecosystem services. The activities carried out within the framework of the NAIAD project showed that, by enhancing the interaction mechanisms, ambiguity in problem frames can still yield collective actions for NBS implementation.

1. Introduction

Nature-based solutions (NBS) have become not only a complementary but a valid alternative to gray infrastructures for coping with

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climate-related risks in urban and rural areas alike (Calliari et al., 2019a; Frantzeskaki, 2019). As defined by the European Commission, NBS are solutions inspired and supported by nature that are cost-effective and capable to simultaneously provide environmental, social and economic benefits and help build resilience. Several examples of NBS for dealing with climate-related risks are cited in the scientific literature (Faivre et al., 2017; Wild et al., 2017; Krauze and Wagner, 2019; van der Jagt et al., 2019). Examples of NBS are restoring wetland, restoring and protecting forests, renaturing watersheds, creating natural retention areas, creating groundwater recharge areas. Catalogues and of available NBS were defined in EU funded research projects – e.g. UrbanGreenUP (https://www.urbangreenup.eu); ThinkNature (www. https://www.think-nature.eu/).Moreover, NBS are increasingly recognised for their capacity to support ecosystems functions and to generate ancillary environmental, economic and social benefits considered as essential backbones of actions for climate-change mitigation and adaptation (Bain et al., 2016; Kabisch et al., 2016; Josephs and Humphries, 2018; Cohen-Shacham et al., 2019). Despite the increasing numbers of methods and tools for supporting NBS design, the transition from designing to implementing NBS remains a challenge due to several barriers (Calliari et al., 2019a; Wihlborg et al., 2019). Some authors demonstrated that physical barriers are less significant than those related to governance, socio-institutional and economic dimensions. Frequent constraints to NBS implementation include the difficulties in activating economic and technological resources, the failure in elevating NBS implementation as a political priority, the lack of horizontal and vertical cooperation between different administrative levels and the failure in activating partnerships between public agencies and private actors (Calliari et al., 2019b). Others (e.g. O'Donnell et al., 2017) showed that the lack of knowledge concerning the NBS impacts – i.e. limited capability to identify and evaluate the multiple NBS benefits and co-benefits – could hamper their implementation because it becomes difficult to justify the financial investments in NBS implementation. Finally, the social acceptance and the low level of stakeholders' engagement were described as barriers by several authors (Calliari et al., 2019b; Giordano et al., 2020; Pagano et al., 2019; O'Donnell et al., 2017).

The present work contributes to this debate by focusing on the collaboration barriers (Calliari et al., 2019b). NBS implementation is a complex issue, whose effectiveness does not depend exclusively on the capacity and resources of the involved decision-agents and the number and quality of the relationships among the different actors involved/interested in NBS implementation (Therrien et al., 2019). Nevertheless, ambiguity in values, preferences and problem frames may lead to collaboration structures that encourage stakeholders and decision-agents to avoid each other, turning the participatory process into a controversial and futile process (Brugnach and Ingram, 2012; Giordano et al., 2017a, 2017b; Howe et al., 2014; Jacobs et al., 2016; Small et al., 2017; Wam et al., 2016; Shrestha and Dhakal, 2019). This, in turn, could result in a barrier to NBS implementation (Eisenack et al., 2014; Therrien et al., 2019). Divergent views about NBS and the expected effects might lead to conflict if the decision-agents and stakeholders perceive the NBS implementation directly affecting their interests (Matland, 1995). Therefore, actions are needed to enable the transition from conflict to cooperation for NBS implementation.

Most of the existing approaches consider ambiguity in problem framing a barrier to collaboration (Herrera-Viedma et al., 2002; Giordano et al., 2007; Liu et al., 2019). These works neglect the network of interactions in influencing decision-makers' problem frames, values and preferences. Individuals do not make decisions in a vacuum, but social interactions can alter preferences, choices and decisions (Kolleck, 2013; Siegel, 2009; Sueur et al., 2012). In multi-agents decision-making processes, differences in problem frames are unavoidable. Ambiguity refers to a type of uncertainty indicating the discrepancies in meaning and interpretation concerning a particular issue (Brugnach and Ingram, 2012). In ambiguous problem frames, the transition from conflict to cooperation claims for actions that stabilise the interactions among the different decision-agents and stakeholders (Matland, 1995). Different decision-agents tend to align their problem frames by interacting, adjusting goals and actions to achieve mutual benefits (Brugnach et al., 2011; Dewulf et al., 2009; Dewulf and Bouwen, 2012). Effective collaboration may occur between decision-agents with a somewhat different problem frame and good relationships (Liu et al., 2019).

The main scope of our work is to demonstrate that actions are needed to enhance the collaboration among stakeholders and decision-makers to effectively implement NBS. Two main research questions guided our work: i) To what extent and in which conditions ineffective interaction mechanisms among decision-agents could hamper the NBS implementation due to conflicts among decision-agents? ii) Do actions for enhancing the effectiveness of the interactions among decision-agents enable the transition from conflict to cooperation in NBS implementation? Concerning the latter, we refer to the networking intervention approach (Valente, 2012). Network interventions are based on the diffusion of innovations theory, which explains how new ideas and practices spread within and between communities. Network interventions are purposeful efforts using social network characteristics to generate social influence, accelerate behavioural changes, and enhance organisational performances through punctual interventions in specific network nodes that could act as leverage points in the system (Calliari et al., 2019a, 2019b; Valente, 2012).

A novel participatory modelling methodology based on the combination of Social Network Analysis (SNA) and a hybrid Agent-based Model/System Dynamic Model (ABM-SDM) is described in this work.

2. Materials and methods

2.1. NBS for protecting groundwater in the Medina del Campo demonstration site

The main scope of this work is to enable the implementation of NBS for protecting Medina del Campo Groundwater Body (MCGB), that is one of the demonstration sites for the EU funded project NAIAD (www.NAIAD2020.eu). MCGB is located in the Duero River Basin, North West central Spain. It covers a surface of 3700 km^2 extending over four provinces that host over 154 municipalities (CHD, 2014). Agriculture plays a main role in the local economy, particularly in the rural areas, being irrigated agriculture the main water use (96%) followed by urban consumption and industrial uses. The site has a low average precipitation and is prone to periodic drought spells. As a result, surface water resources are scarce, with only three seasonal surface water courses that have limited intermittent flows along the year. Therefore, the water supply and the economy of the region heavily depend on the aquifer. There are currently 5495 groundwater concessions for agricultural use issued over a surface of 451 km^2 of irrigated area (CHD, 2014). The most common irrigated crops are: maise, beetroot, cereals, vineyards, and potatoes. The most diffuse non irrigated crops are: cereals (wheat, barley), sunflower, and legumes (www.ine.es; http://naiad2020.eu/wp-content/uploads/2018/07/D6_1.pdf).

The intensive exploitation of MCGB over the last decades has put the groundwater body at risk from both the qualitative and quantitative standpoints according to the requirements of the Water Framework Directive (WFD 2000/60/EC), while seriously impacting the associated surface ecosystems. Meanwhile, droughts also cause severe economic losses in agriculture that are contributing to a severe decrease in rural population. Medina del Campo was one of the case studies of the project NAIAD, whose implementation aimed at assessing the potential and impacts of a series of selected NBS to reduce the effects of more frequent drought episodes due to climate change. Moreover, the NBS implementation aims at controlling the degradation of the groundwater status and associated ecosystem services. During NAIAD project implementation, two NBS were selected, i.e. the Managed Aquifer Recharge and the Crop change (Pengal et al., 2017). Within the NAIAD framework, the main scope of our work was to enable the transition from NBS design toward implementation by detecting and analysing potential barriers. To this aim, the different methodological phases described in Table 1 were implemented in this case study.

2.2. The multi-methodology for overcoming collaboration barriers

The multi-methodology described in this work aims at enabling the NBS implementation by detecting, analysing and overcoming the barriers hampering the collaboration among different decision-agents.

Two primary methodologies were adopted. I.e. the SNA allowed us to map the complex web of interactions – both formal and informal – among the different decision-agents in NBS implementation. SNA was also adopted as a diagnostic tool to support detecting the key vulnerabilities in the interaction networks and the nodes in which actions ought to be implemented to reduce the detected vulnerabilities. Despite its benefits, SNA does not explain how those vulnerabilities could lead to collaboration barriers to NBS implementation.

A hybrid ABM-SDM approach was adopted in this work with a two-fold role. On the one hand, it allowed us to investigate to what extent the key vulnerabilities in the network of interactions among the different decision-agents affect the NBS implementation and effectiveness. On the other hand, the hybrid ABM-SDM allowed us to simulate and compare different interventions scenarios, identifying the most suitable networking interventions, i.e. actions for overcoming the detected collaboration barriers.

Stakeholders were engaged in four activities: i) individual semi-structured interviews were carried out for behavioural model definition – i.e. how do decision-agents behave? What kind of decisions do they take? What are the conditions affecting their decisions? What information do they use?; ii) a participatory mapping exercise was organised aiming at developing the map of interactions, i.e. a graph showing the existing – formal and informal - interactions among the different decision-agents interested/involved in NBS implementation; iii) a second round of interviews was carried out for testing and validating the model; iv) a participatory workshop was organised with the aim of co-defining the networking interventions, i.e. actions to be implemented to overcome the enable collaboration among the different decision-agents. The frameworks adopted for facilitating the stakeholders' engagement in these activities are described in the Section S3 of supplementary material.

2.2.1. SNA for detecting the key vulnerabilities in the network of interactions

Combining SNA and ABM is not novel in modelling complex environmental systems. It aims to analyse the role of social structure and its dynamics in influencing agents' behaviour. The combination between SNA and ABM has two primary purposes, i.e. diffusion and social integration (Will et al., 2020). In the former type of approaches, the agents are linked in a network to simulate material and/or information transfer. This approach allows to model how new ideas and practices spread within a specific community of agents through interpersonal relationships (Valente, 2005; Rasoulkhani et al., 2018). In the second kind of approaches, social structures are seen as a form of coordination enabling collective action. These SNA-ABM models investigate how the position of an agent within a network provides social capital, which allows specific actions and achievements (Will et al., 2020) Our work combines these two approaches since it aims at both analysing the social influence on the dissemination of attitudes and assessing the effectiveness of the network structure in enabling cooperative decision-making.

SNA represents networks of people as graphs and exploring these graphs to detect patterns of connections (Powell and Hopkins, 2015). People are represented as nodes in this graph, connected through ties of different strengths (Furht, 2010). The strength of the ties depends on the characteristics of the connections – i.e. frequency, intensity, importance, etc. (Borgatti, 2006; Ingold, 2011). SNA has the potential to support the definition of networking interventions by unravelling the complexity of the interaction network affecting the multi-actors decision-making process for NBS implementation and allowing the identification of the nodes that play a central role in the process (Calliari et al., 2019b; Kolleck, 2013; Therrien et al., 2019). SNA can help understand how and why the actors behave the way they do by analysing structural patterns of relations that influence social processes (Borgatti and Foster, 2003).

In this work, SNA was implemented to make explicit formal and informal networks of interactions in which the different decision-agents dealing with NBS implementation are involved. Among the various methods available in the scientific literature for modelling and analysing the social networks (e.g. Borgatti, 2006; Ingold, 2011; Lienert et al., 2013), the Organisational Risk Analysis (ORA) approach has been adopted in this work (Carley, 2002). While most of the existing methods for SNA implementation in multi-actors' decision environment focused exclusively on interaction among actors and on the role of the trust among them (e.g. Liu et al., 2019), ORA assumes that the interaction among decision-agents is mediated through other elements, such as tasks and information. Effective cooperation among decision-agents requires actors to cooperate in carrying out certain tasks and exchange information (Giordano et al., 2017a, 2017b). The ORA approach is based on interlocked networks represented using the meta-matrix conceptual framework, as shown in Table 2.

A participatory mapping exercise was designed to map the network of interactions among the different stakeholders and the connection with the information and the tasks, involving institutional and non-institutional decision-agents having a stake in the GW management and protection (Table 3).

During the mapping exercise, participants were requested to mention each actor's tasks to carry out in NBS implementation. Links were drawn connecting actors and tasks. Then participants were asked to specify with whom the different actors were supposed to cooperate to

Table 1
The different steps composing the adopted methodology.

Phase of the methodology	Scope	Method/tool	Software used
Social Network Analysis	Mapping the interactions between decision-agents and stakeholders Detecting the key vulnerabilities in the interactions network	Group mapping exercise Organisational Risk Analysis Graph Theory measures	ORA-LITE © (http://www.casos.cs.cmu.edu/projects/ora/software.php)
Hybrid ABM-SDM	Eliciting and structuring the actual behaviours of the different decision-agents Formalising and coding the agents' behaviours Validating the model Detecting and analysing potential conflicts Analysing the impacts of conflict on NBS implementation Simulating interventions scenarios Prioritisation of the networking interventions	Individual interviews Decision trees Fuzzy inference Hybrid ABM-SDM Scenario simulation and analysis	MATLAB© Fuzzy designer ISEE-systems Stella Architect

Table 2
Meta-matrix framework showing the connections among the key entities of social network (adapted from Carley (2002)).

	Agent	Knowledge	Tasks
Agent	*Social network:* map of the interactions among the different decision-agents in NBS implementation.	*Knowledge network:* this network describes the relationships among actors and information (Who does manage which information? Who does own which expertise?)	*Assignment network:* this network defines the role played by each actor in the NBS decision-making process
Knowledge		*Information network:* map of the connections among different pieces of knowledge used/needed in the NBS decision-making process.	*Knowledge requirements network:* this network identifies the information used, or needed, to perform a certain task in the NBS decision-making process
Tasks			*Dependencies network: this network* identifies the workflow. (Which tasks are related to which)

carried out the defined tasks. Finally, the information was introduced in the map. Participants connected the different kinds of information with the tasks this information was supposed to support (knowledge requirements network), and the actors owning/using the information (knowledge network). Once the map describing the Agents-Information-Tasks connections was developed, participants were requested to assign an importance degree to each link according to their own understanding. Three different values were used in this phase, i.e. "High importance" (+++ in the map), "Medium importance" (++ in the map), "Low importance" (+ in the map). Fig. 1 shows the results of the participatory mapping exercise.

The obtained maps were coded using the ORA-Lite© software and analysed to detect the main vulnerabilities of the network of interactions through the implementation of graph theory measures. In this work we assumed that a network vulnerability can be due agents (e.g. a key actor is rather marginal in the network), information (e.g. important information is not adequately shared), and tasks (e.g. due to a limited level of cooperation) or a combination of the three categories. The following graph theory measures were implemented (Table 4). For a more extensive description of the graph theory measures, a reader could refer to Freeman (1978) and Carley et al. (2007).

This analysis allowed us to detect the key vulnerabilities in the interaction network and the agents impacted by the weak interactions, as described in Section 3.

2.2.2. Modelling decision agents' behaviours for detecting barriers to NBS implementation

This phase aimed at investigating to what extent the key vulnerabilities in the network of interactions detected through the SNA, could create collaboration barriers to NBS implementation. To this aim, a hybrid ABM-SDM modelling approach was adopted to formalise and code the decision-agents' behaviours and to assess the impacts of the interactions on their decision-making processes. Hybrid ABM-SDM combines the potentialities of ABM and SDM and allows overcoming their main pitfalls (Wang et al., 2018).

On the one hand, ABM is a modelling approach allowing the computational study of autonomous agents that can interact with each other and their environment (Castilla-Rho et al., 2015; BenDor and Scheffran, 2019; Huber et al., 2021). ABM has been largely adopted in modelling environmental resources management and policy implementation because of its capability to incorporate human behaviour into modelling and to represent individual decision-making, the interactions among the different decision-agents and with their environment, and to detect unintended consequences due to the complex interactions (Jenkins et al., 2017; Lorscheid et al., 2019; Schwarz et al., 2020; Zhuge et al., 2020; Huber et al., 2021). ABM is a bottom-up modelling approach, in which the macro-response at the system level depends on the aggregation of individual agents' behaviours. It often ignores the continuous feedback between the individuals and the whole system (Lorscheid et al., 2019). On the other hand, SDM is based on the representation of a system in terms of interlaced feedback loops connecting the different variables and providing information on the system's dynamic behaviour (Sterman, 2000). In SDM, the system is modelled as a single item through state variables. SDM does not seem suitable to simulate systems characterised by some level of heterogeneity (Vincenot et al., 2011).

The hybrid ABM-SDM approach allows to model complex systems as composed of entities that are simultaneous "wholes" unto themselves while being a "part" in the larger system (Vincenot et al., 2011). Hybrid ABM-SDM considers agents' behaviour and the system-level features as inseparably linked (Lorscheid et al., 2019).

ABM and SDM can be combined by embedding SDM within each agent or embedding agents within an SDM. In the first case, the whole system is conceptualised as interacting agents, whose behaviour is formalised as SDM. In the second case, the dynamic evolution of the whole system is captured using SDM and some parts are described as ABM. In this work, we decided to adopt the first type of combination. That is, the agents are firstly influenced by the interactions among themselves and with the environment. Then, the results of these interactions are elaborated according to their behavioural rules, structured as SDM (Vincenot et al., 2011; Giabbanelli et al., 2017).

Table 3
List of stakeholders involved in the participatory mapping exercise.

Stakeholder	Role in the process
Farmers	Individual farmers who hold a water right entitling them a certain maximum volume of water for irrigation per year.
Farmer associations	Farmer Unions representing the interest of farmers in the different municipalities around Medina.
Irrigation communities/WUAS	Communities composed by nearby farmers that share common irrigation infrastructure or groundwater rights and have self-management capabilities.
Local government: municipalities	Local institutions responsible for defining policies related to: i)city planning; ii) water supply; iii) flood and drought management support.
Regional government (Junta Castilla y León)	Regional institution responsible for regional planning in natural areas; environmental quality; sustainable development strategies at regional level; agricultural development; civil protection
Duero River Basin Authority	Main problem owner due to law. It has responsibility for taking care of national water public domain; water planning; water rights issuer; compliance with WFD, Floods Directive, water quality standards.
Local NGOs	Bottom-up organisations active in the study area with the cope of denouncing the lack of environmental protection compliance, and the creation of public awareness
Academics from local universities	Research institutions dealing with water risks
Insurance sector (Agroseguro, Consorcio de Compensación de Seguros)	Economic actors providing insurance to farmers

Fig. 1. Results of the participatory mapping exercise.

The "Overview, Design concepts and Details" (ODD) (Grimm et al., 2020; Grimm, 2020) protocol was used for developing and describing the hybrid ABM-SDM. The ODD protocol requires to specify the agents to be included in the model, their attributes and behavioural rules – i.e. which agent does what, which rule is implemented by agents for taking decision or changing their state, what are the elements of the environmental that affect the agents' behaviour (Mehryar et al., 2019). In this work, the rules of interaction among the different agents and between them and the environment were derived by the SNA. The agents' attributes and behavioural rules were elicited through semi-structured interviews and coded in SDM. A full ODD description is reported in the supplementary material S1. Here we describe the key characteristics of the hybrid ABM-SDM model.

2.2.2.1. Agents. The model is composed of three decision-agents and one environmental agent. The decision-agents are: i) a community of farmers; ii) the WUA; iii) and the controller agent, CHD. The environmental agents is the groundwater (GW). For the sake of simplicity, we did not include the market as part of the environment affecting the agents' decisions. We assumed here that the market is always favourable for the irrigated crops and the farmers' decisions are mainly influenced by the state of the GW.

A population composed of 100 farmers was created and clustered in two groups: large farmers and small-medium farmers. The population is composed of 20 large farmers and 80 small-medium farmers. This reflects the actual partition in the study area (www.ine.es). In this first version of the model, the farmers do not have spatial distribution. Farmers were assigned a cropping strategy, composed by the kind of crops and the water volume allocated for irrigation purposes (Table 5).

The CHD is a controller agent whose role is to monitor and assess the GW's state, assign water rights to the farmers, and impose limits to GW use in case of overexploitation. The WUA acts as an interface between the farmers and the CHD.

2.2.2.2. Process overview. The time step is one year. Within each time step, the process is regulated by the interactions among the agents, defined using the SNA results and described in Table 6.

As an initial step, CHD controls the GW's state and decides whether to enforce limits to GW use or not accounting for GW exploitation index. This decision affects the farmers' assessment of the GW availability. Farmers check the groundwater availability and the expected productivity and define the cropping strategy. If a change in the strategy is needed, farmers enter in a decision-making process in which three alternative courses of actions are available: i) selecting a more sustainable crop (less water demanding); ii) ignoring the CHD limits and keeping

Table 4
Graph theory measures for detecting key vulnerabilities in the network of interaction.

Graphical measures	Meaning in NBS implementation
Centrality degree in the Social Network Centrality degree in the Knowledge network Centrality degree in the Assignment network	An agent with a few and weak connections with the others (low level of centrality) would not be capable to carry out important tasks and share key pieces of knowledge
Most knowledge in the Knowledge network Centrality degree in the Information network Centrality degree in Know. Requirement net.	A piece of knowledge can be considered as important in the process if it enables the access to other pieces of knowledge and allows the fulfilment of several tasks. However, a low most knowledge measure means that it has a low level of access for many agents, i.e. it is not adequately shared.
Most task in the Assignment network Centrality degree in the Dependencies net.	A task with a high centrality degree must be carried out in order to enable the fulfilment of the other tasks. A low Most task measure means that this key task is not cooperatively performed. The risk of failure is high, leading to the impairment of the other tasks.

Table 5
Farmers' strategies at the beginning of the model simulation.

Kind of farmer	Type of crop (irrigated and non-irrigated)	Water volume used
Large farmers	80 ha: 20 ha irrigated and 60 ha non irrigated	3000 m^3/ha
Medium-small farmer	30 ha: 10 ha irrigated and 20 non irrigated	3000 m^3/ha

Table 6
Existing interaction among the different agents.

Agent	Affected by whom – how	Affects who - how
GW	Climate condition – recharge rate Farmers – exploitation rate CHD – protection policies	CHD – declaration of overexploitation Farmers – irrigation strategy (availability)
Farmers	CHD – water rights policies CHD – GW information GW – available water for irrigation WUA – information sharing	GW – use of the resource CHD – protection of the GW
WUA	Farmers – information sharing	CHD – control of the territory
CHD	GW – declaration of overexploitation Farmers – control of the territory	Farmers – limits to GW use Farmers – GW info sharing Farmers – Water rights process GW – protection policies

the GW use at the initial level (illegal behaviour); iii) abandoning the cultivated areas. The conditions influencing this decision-making process are described further in the text.

WUAs were still under development at the time of our analysis. Therefore, we decided to account for the interaction between the WUA and the other agents in the model. However, we were not capable of simulating the behaviour of this decision-agent.

2.2.2.3. Agents' behaviour. Individual semi-structured interviews were carried out to build the decision-agents' behavioural rules. Referring to the work described in (Mehryar et al., 2019), the interviews aimed at enhancing the understanding of the actual behaviours of the decision-agents in terms of: i) key objectives to be achieved; ii) alternative actions to be implemented; iii) conditions influencing the selection of the different actions (see supplementary material for further details about the framework used for the interviews).

The collected decision-agents' argumentations were analysed and structured into decision trees. This phase was guided by the behavioural decision-making theories described in (Schlüter et al., 2017; Schwarz et al., 2020), which were used for interpreting and coding the agents' behaviours (Table 7).

Fig. 2 shows the decision tree concerning the initial farmers' decision: whether to keep the same cropping strategy of the previous year or change it.

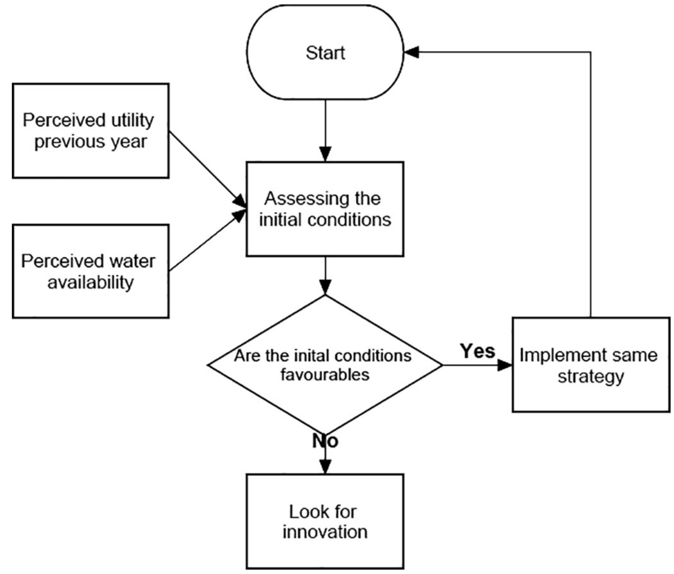

Fig. 2. Initial farmers' decision tree concerning the need to change the cropping strategy.

According to the bounded rationality theory, farmers take this decision referring to their perception of the initial conditions, which is affected by two key elements: the previous year's utility and the expected water availability. Concerning the latter, we learned that farmers estimate the water availability at the beginning of the irrigation season, accounting for the water right, the water volume allocated by the CHD to each farmer (see the description of the CHD behaviour for more details). If the assessment of the initial conditions is favourable then farmers implement the same strategy of the previous year, otherwise farmers will look for a new strategy entering in a new decision-making process. This behaviour is consistent with the reinforcement learning theory (Schlüter et al., 2017).

When seeking an innovation, farmers' behaviour differs according to the size of the farm. Medium-small farmers do not have great innovation potentialities. Most of the time, the innovations are introduced in the community by other farmers, spreading through social interactions. The tighter the social connections and the faster is the innovation spread process. This behaviour is coherent with the descriptive norm decision-making theory (Schlüter et al., 2017). The farmer observes the others and derives a dominant behaviour. Its perception of the dominant behaviour will make this behaviour more salient for the agent. However, adopting the descriptive norm behaviour depends on the social attitude of farmers and the level of trust toward the CHD.

Fig. 3 shows the decision tree concerning this part of the farmers' behaviour.

On the one hand, the low level of trust toward CHD and the lack of social capital - i.e. limited interactions within the farmers' community - leads farmers to act as almost isolated agents. We learned during the

Table 7
Decision-making theory and observed behaviours.

Agent	Decision theory	Decision	Observed behaviour
Farmer	Bounded rationality	Crop selection; Irrigation strategy	Farmers do not have full knowledge of their environment. They make decisions based on their perception of key elements, i.e. productivity and water availability. Moreover, the selection of the alternatives is based on a satisfactory threshold.
	Reinforcement learning	Crop selection; Irrigation strategy	At the beginning of the irrigation season, farmers tend to confirm the strategies adopted in the previous year if they allowed farmers to achieve a satisfying utility.
	Descriptive norm	Change crop and irrigation	Once the initial strategies are no longer satisfactory, farmers look for innovation by observing the other farmers, specifically those considered as successful.
CHD	Theory of planned behaviour	Enforce GW limits Territory control Technical support	In these three decision-making processes, CHD acts according to its own assumption about how the farmers will react to its decisions.

interviews that the lack of information sharing and the lack of transparency in water rights assignment affected the CHD reputation and, thus, the level of trust. Moreover, the lack of WUA formation affects the farmers' social capital since it reduces the chance of creating and sustaining interactions among farmers.

At this stage, two elements affect the farmers' decision, i.e. the acceptance of the water rights and the perceived control of the territory. Both elements are affected by CHD reputation. As shown in Fig. 3, in case of a low level of acceptance and a weak perception of territory control, farmers tend to keep the same crop and to increase GW exploitation using their wells. This behaviour is against the CHD rules and will affect the state of the GW.

On the other hand, socially oriented farmers act according to the normative behaviour. Therefore, they look for dominant behaviour within their community. They tend to accept innovations suggested by other farmers or by the WUA (technical support for cropping change). In these conditions, farmers likely select less water demanding crops (sustainable crops). If the innovation is not available in the farmers' community, farmers decide to reduce the irrigated crops. However, in the long term, this strategy affects the economic sustainability of the farm.

The medium-small farmers' decision tree was coded into SDM for simulating their behaviours. Fig. 4 shows the developed SDM.

The main goal of the SDM in Fig. 4 is to simulate the medium-small farmers' behaviour concerning: i) the adoption of sustainable cropping strategies; ii) the adoption of illegal behaviour in GW use; and iii) the abandonment of the irrigated agriculture. The SDM is composed by three sub-modules that formalise the processes activated by the farmers to take specific decisions. Sub-module A describes the farmers' behaviour related to the adoption of innovations in agricultural practices. Sub-module B is meant to formalise the farmers' decision concerning the formation of WUA that, in turn, affects the farmers' social capital and the acceptance of the water rights. Sub-module C simulates the farmers' decision to adopt or not an illegal behaviour in GW use for irrigation.

Three kinds of variables characterised the SDM. i) The stock variables describe the possible agents' states. These variables allow simulating the transition of the small farmers from one state to the other. ii) The flow variables describe the transition process of the farmers population from one state to the others. iii) The rate at which these transitions happen in the SDM is controlled by the converter variables (shown as circles in the SDM), representing the conditions affecting the small farmers' decision, as described in the decision tree. This SDM is

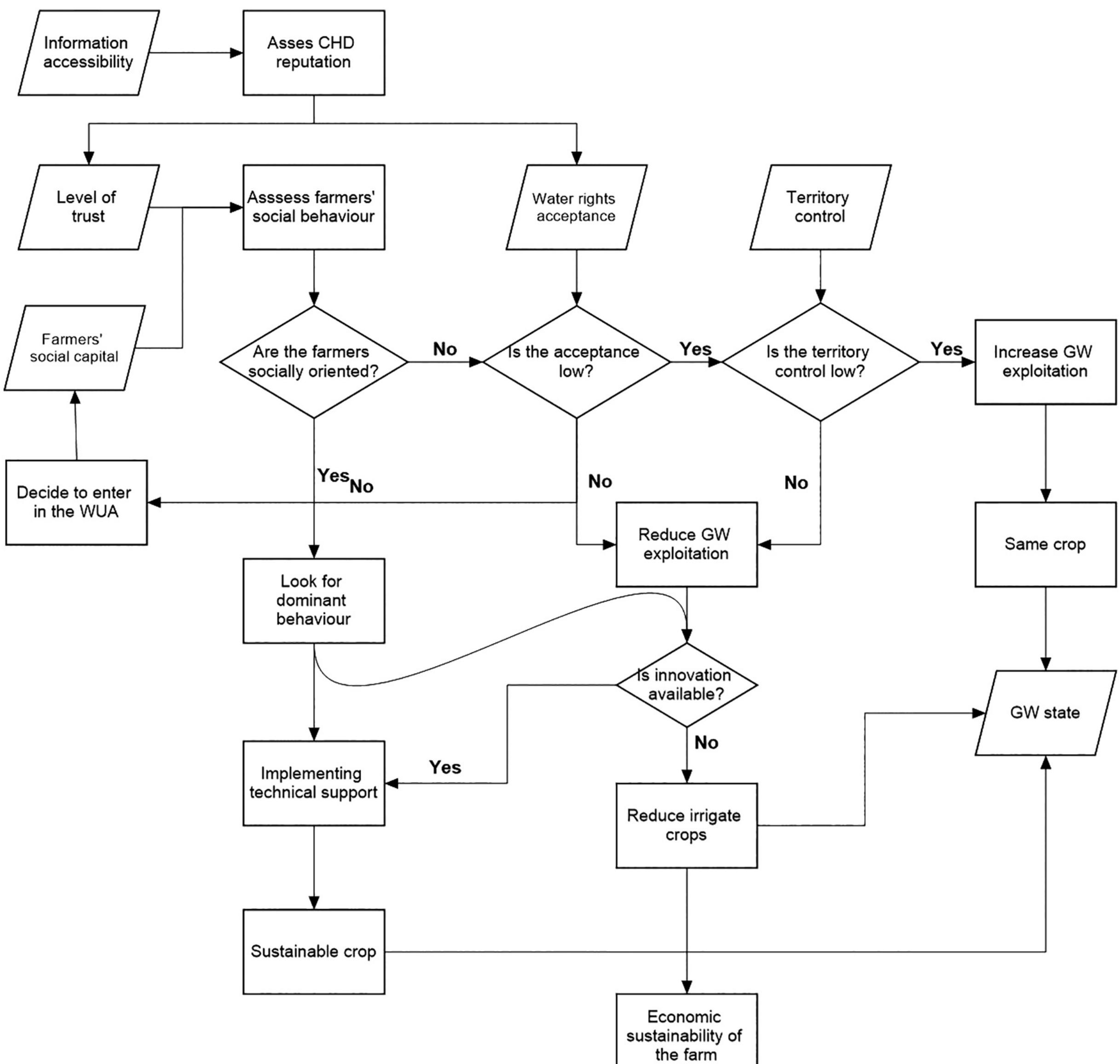

Fig. 3. Farmers' decision tree concerning the change of strategy and illegal behaviour.

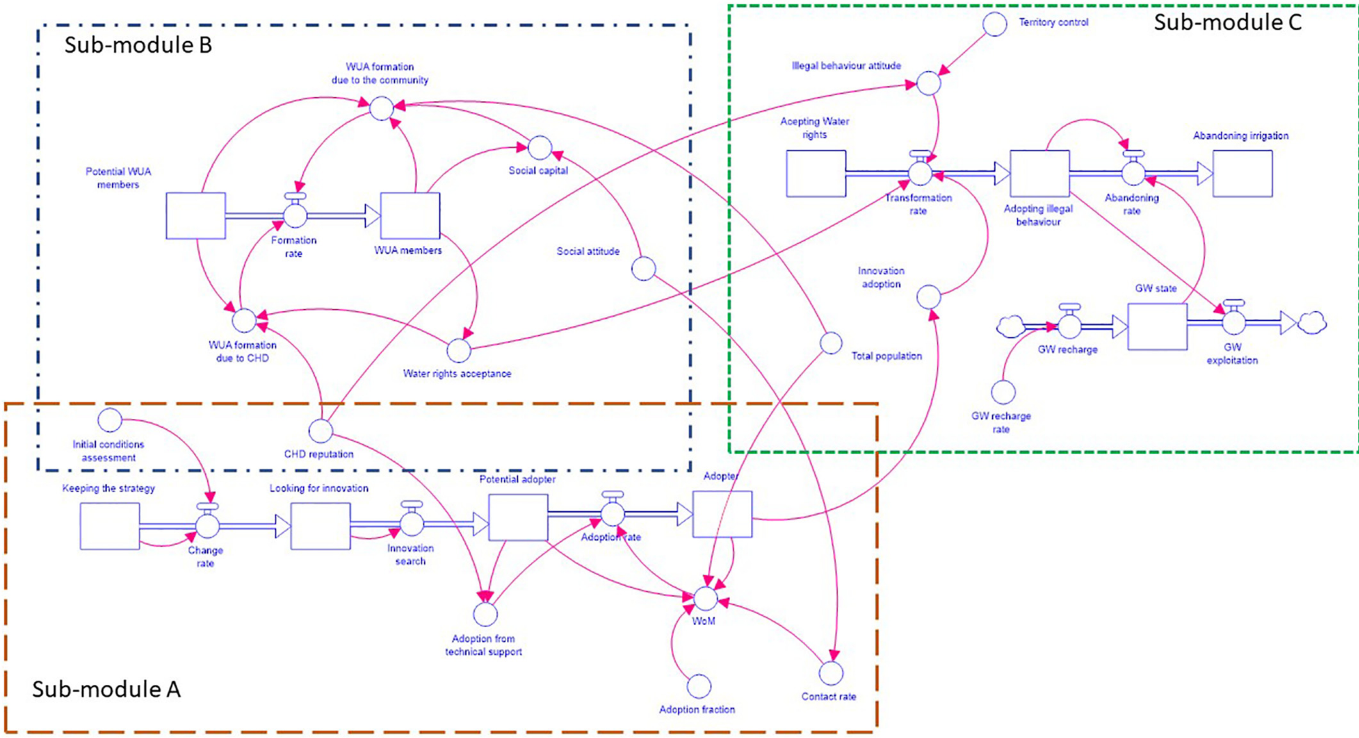

Fig. 4. SDM describing the small-medium farmers' behaviour.

connected to the other agents' SDM – i.e. CHD (controller agent) and GW (environment agent) – through specific variables, showed as double-circled variables in Fig. 4. Refer to Supplementary material S1 for a detailed description of the interaction among the agents' SDM.

For the sake of clarity, we could consider the sub-module A. It shows the transition of the farmers from the initial state "keeping the strategy" toward the state "looking for innovation". The transition is affected by the assessment of the initial conditions, as shown in Fig. 2. If farmers decide to look for innovation, they enter in the state "potential adopter". The farmers' decision to adopt an innovation - i.e. changing the state from "potential adopter" to "adopter" - is influenced by the availability of technical support and by the "word-of-mouth" diffusion mechanism. The latter refers to the capability of farmers to influence the other members of the community. This innovation mechanism is influenced by the farmers' social attitude that affects the contact rate, which defines the number of others with whom the farmer interacts and exchanges information. That is, the more socially oriented is the farmer and the higher is the contact rate. As described previously, the farmers' social attitude is affected by trust and social capital. A farmer will meet and exchange information within the community according to the number of contacts (social capital) and the level of trust. The main equations describing the dynamic evolution of the different variables are described in the ODD (supplementary material S1).

The MATLAB© fuzzy inference engine, based on fuzzy *if....then* rules was adopted for assessing the values of the variables describing the rate of transition between two states. This is mainly because fuzzy *if… then* rules are suitable for simulating the human reasoning process leading to a decision without simplifying the human behaviour. Fuzzy rules are capable of accounting for the imprecise nature of human reasoning based on the knowledge that is neither certain nor consistent (Zadeh, 1983). The following fuzzy *if…then* rules were developed for the variable "initial conditions":

If (Previous Utility is Low) and (Water Availability is Not Sufficient) then (Initial Conditions is Not Favourable).

If (Previous Utility is Low) and (Water Availability is Sufficient) then (Initial Conditions is NotFavourable).

If (Previous Utility is Medium) and (Water Availability is Not Sufficient) then (Initial Conditions is Not Favourable).

If (Previous Utility is Medium) and (Water Availability is Sufficient) then (Initial Conditions is Favourable).

If (Previous Utility is High) and (Water Availability is Not Sufficient) then (Initial Conditions is Not Favourable).

If (Previous Utility is High) and (Water Availability is Sufficient) then (Initial Conditions is Favourable).

The if-part of the rule is defined as the "antecedent" or "premise", and it is composed by the conditions at the basis of the farmers' decision, i.e. "Previous Utility" and "Water Availability". The then-part is defined as the "consequent" or "conclusion". In this case, the rule's conclusion represents the possibility that the farmers consider the initial conditions as favourable. Fuzzy inference is the process of forming inferences and drawing conclusions. Fuzzy linguistic functions were developed by interacting with the farmers and associated to the antecedent and consequent (Page et al., 2012) (see supplementary material). The fuzzy operators AND is used to define the value of the antecedent. The result of the antecedent is then applied to the consequent (also known as implication). The final value is obtained by aggregating all consequents across the rules (Zimmermann, 1991). Contrary to traditional - i.e. boolean - inference methods, in which a rule can be either true or false, in fuzzy inference, the rules could all be true with a different degree of belief (Zimmermann, 1991). In this work, the Mamdami inference and the centroid defuzzification methods were applied for inferencing the result of the fuzzy rules.

The fuzzy inference allowed us to define the farmers' assessment of the initial conditions (Fig. 5).

The defuzzified value of the "initial conditions" - i.e. 0.71 in Fig. 5 - is the value used in the SDM for the variable "initial conditions". Similarly, fuzzy *if…then* rules were developed for the other variables influencing the transitions of the decision-agents from one state to the other.

The big farmers are characterised by rather different behaviour. During the interviews, we learned that they had a high-level trust toward the CHD and the water rights assignment. Moreover, they had enough resources for collecting updated information about the state of the

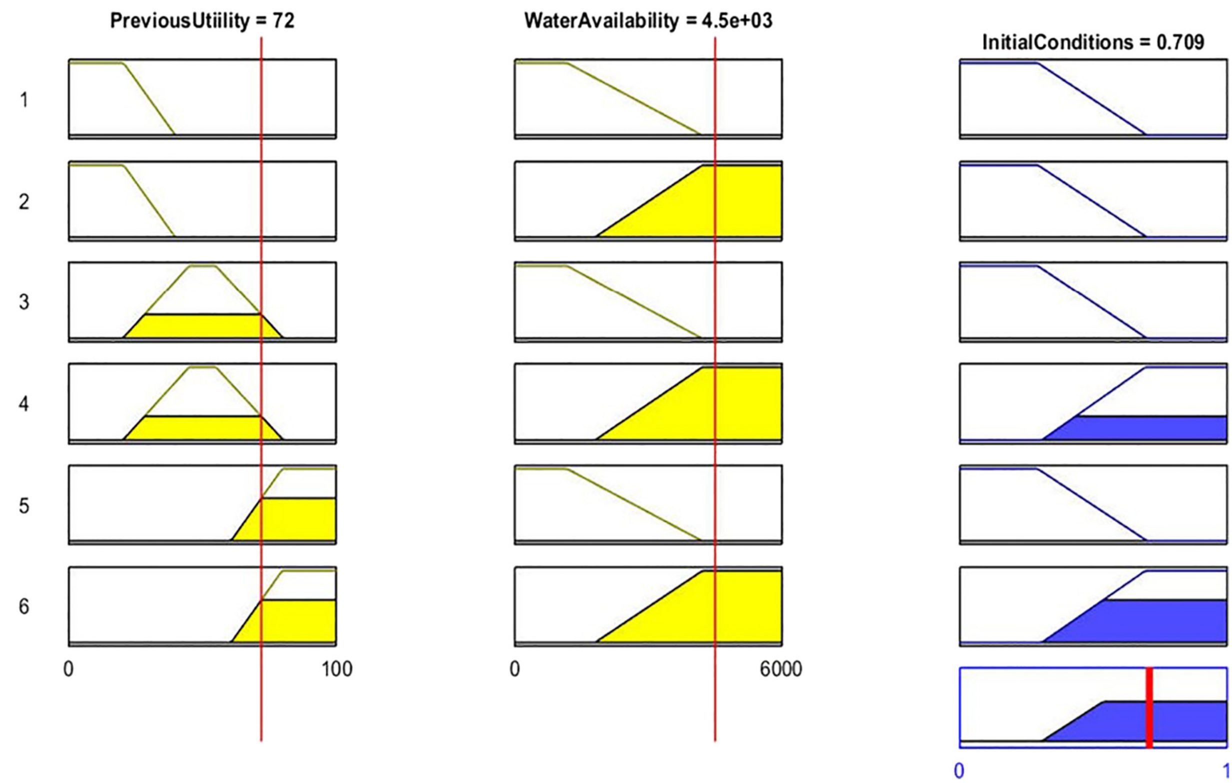

Fig. 5. Assessment of the "initial conditions" accounting for the utility of the previous year and the expected water availability. In this example, we assume the farmers perceived a utility equal of 72 and expected to have 4500 cubic meter per ha (mc/ha). The "initial conditions" has a value of 0.71.

GW. If the habitual strategy fails due to limited water availability for irrigation, big farmers check the GW state. If the state is good, big farmers apply for new water rights. If the GW is overexploited, CHD will not release new water rights. In this case, the big farmers will introduce innovations in the irrigation system in order to optimise the volume of water available for irrigation. Finally, in the case of prolonged limitation in GW availability, big farmers will have the economic resources to adapt to the cropping strategy. The big farmers act as boundedly rational agent.

2.2.2.4. CHD. CHD is the controller agent, whose main scopes are: 1) to assign water rights to the farmers allowing them to use GW for irrigation purposes; ii) to impose limits to GW use; iii) to control the territory for detecting illegal behaviours. Three members of the CHD were interviewed to define the behaviour of this decision-agent. Specifically, the responsible for the water rights assignment, the responsible for the groundwater monitoring and quality assessment, and the responsible for the irrigation management plan.

Two main elements influence CHD decisions. Firstly, CHD assesses the GW exploitation index based on the GW recharge and the expected GW use. If this index is <0.88, then CHD can distribute the water rights. In this model, we assume that water rights are equally distributed. Another key decision of this agent concerns the enhancement of the territory control through remote sensing techniques. This decision depends on the CHD level of trust toward the farmers, which is influenced by two inputs from the farmers' SDM, i.e. the farmers adopting illegal behaviour and the water rights acceptance.

The CHD decision tree and SDM are reported in the supplementary material. CHD seems to behave according to the theory of the planned behaviour. That is, CHD has a set of attributes reflecting its beliefs about the effects of its decisions on the sustainable and equitable use of GW for irrigation. The capability to control the actual implementation of the decision taken - i.e. the enforcement of limitations to GW use and the adoption of sustainable cropping strategies by farmers - is perceived as a key asset by the CHD. The need to control, which is typical of the planned behaviour, leads CHD to enforce sanctions if detected illegal behaviour. In doing this, CHD aims at reducing GW exploitation.

2.2.3. Model validation

A validation phase was needed prior to use the hybrid ABM-SDM for detecting the collaboration barriers and develop scenarios. The main scope of this phase was to assess the capability of the developed model to replicate the behaviours of the different decision-agents. In designing the validation phase, we had to account for the limited availability of historical data for validating the farmers' behaviour. Specifically, the creation of WUAs in the case study was still ongoing at the time of this work. Although data concerning the selection of the cropping strategy were available, it was not possible to collect data concerning the conditions influencing this decision (e.g. the role of the social capital). Finally, there were no historical data on farmers' illegal behaviours in using GW for irrigation. Moreover, it is worth stressing that this hybrid ABM-SDM was not meant to replicate the "real" world, but to provide a formalised description of the decision-agents' behaviours. Therefore, as also pointed out by (Jetter and Kok, 2014), the benchmark for this hybrid ABM-SDM validation was if it adequately described the way decision-agents act in different conditions. This validation method requires an active role of the decision-agents in testing the model. Firstly, a sensitivity analysis was carried out to test the system behaviour varying the values of the input variables. This phase allowed us to check the consistency of the model structure and equations (Pagano et al., 2019). Secondly, a second round of interviews was organised involving the stakeholders already engaged in the model development. The capability of the model to replicate the decision-making processes under different circumstances – i.e. the conditions of fuzzy inference – was discussed (Jetter and Kok, 2014; Pluchinotta et al., 2021). The Behaviour Over Time (BOT) approach was adopted for facilitating the discussion with the stakeholders (Herrera and Kopainsky, 2020). The framework used for this second round of interview is reported in the supplementary material, Section S3.

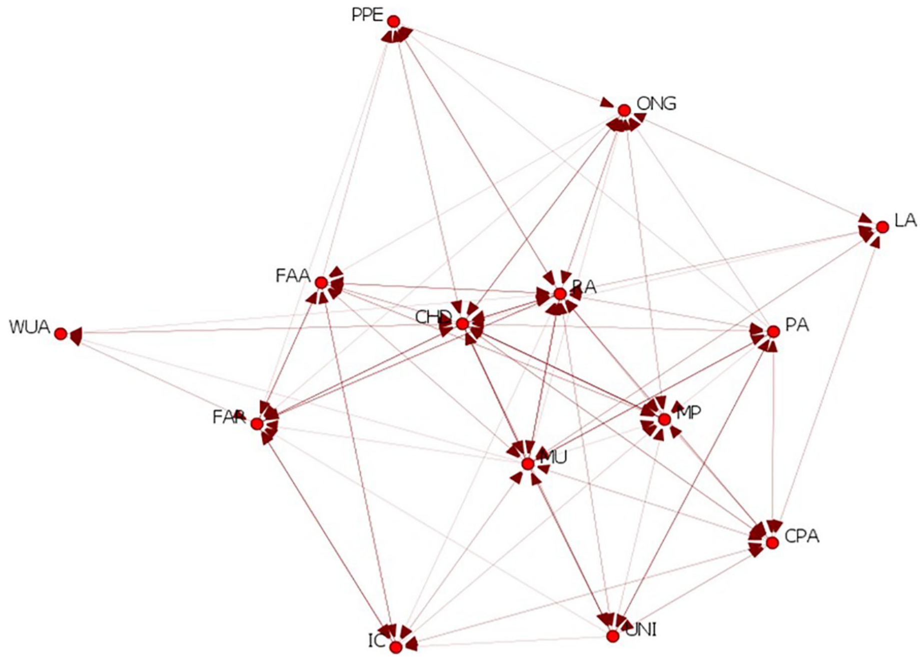

Fig. 6. Social network (Agent x Agent) map of interactions. A different thickness characterises the links according to the weight assigned by the participants. The acronyms in the figure represent the decision-actors mentioned during the participatory mapping exercise. Their meaning is explained in the Section S2 of the Supplementary material.

3. Results

3.1. SNA for detecting the key barriers to collaboration

The results of the participatory mapping exercise were translated into adjacency matrices and, finally, input in the ORA-Lite © software, which was used in this work for analysing the maps. Fig. 6 shows the social network (Agent X Agent network). The connections are characterised by different thickness, representing the weights assigned by the stakeholders.

Table 8
Key vulnerabilities in the network of interactions for Medina del Campo.

Key vulnerabilities	Meaning in the NBS process	Actors involved
WUA	This agent is characterised by a quite low centrality degree in the Agent X Agent network. That is, it has few and weak connections with the other actors. It is supposed to carry out important tasks and has access to important pieces of knowledge.	WUA, Farmers
Water rights management	This task has a high centrality degree in the Task X Task network. Therefore, it enables the fulfilment of other important tasks. Nevertheless, it is connected exclusively with the CHD.	CHD, Farmers
Technical support for crop selection	This piece of knowledge plays a key role in carrying out the most important tasks (Knowledge X Task network). Nevertheless, it has a low Most knowledge degree in the Agent X Knowledge network and, thus, it is not effectively shared in the network.	CHD, WUA, Farmers
GW state information	This piece of knowledge has a high centrality degree in the Knowledge X Knowledge network, which means that it enables access to other important pieces of information. Nevertheless, only a few agents have access to it (Agent X Knowledge network).	CHD, Farmers

The obtained maps were analysed accounting for the graph theory measures described in Section 2. Table 8 shows the key vulnerabilities detected in the network of interactions and the actors involved/impacted by those vulnerabilities.

These results showed that to enhance the collaboration among decision-agents, efforts were required for: i) making the WUA more central in the process; ii) facilitating the co-implementation of the water rights management; iii) enhancing the sharing of the technical information for crop changes; and iv) enhancing the sharing of the information regarding the GW state and the associated risks. The results of the graph theory analysis are reported in the supplementary material.

3.2. Hybrid ABM-SDM simulation for detecting collaboration barriers

The developed hybrid ABM-SDM was validated according to the procedure described in Section 2.2.3. Then, the model was used to investigate to what extent the lack of effective interaction mechanisms affects the agents' behaviour and, thus, hamper the implementation of the NBS in the Medina del Campo case study. The Business-As-Usual (BAU) scenario was simulated to investigate the impact of the vulnerabilities in the network of interactions on agents' behaviour. The BAU scenario is characterised by these assumptions reflecting the current conditions in the case study: i) farmers have no access to information about the GW state; ii) there is a low level of acceptance of the water rights assignment process; iii) farmers do not want to create WUA; iv) a prolonged drought is interesting the Medina area. Moreover, we assume that farmers are characterised by a rather low level of social capital. The limited accessibility of GW information affects the CHD reputation and, thus, the level of trust. Finally, CHD is perceived as not capable of controlling the territory.

The high value of the GW exploitation index leads the CHD to enforce the limitation of water rights. Farmers perceive the initial conditions as not favourable because of the lack of water volume available for irrigation and start looking for innovation. Both innovation mechanisms are ineffective in this scenario due to the lack of trust and the limited social capital. Therefore, the transition toward the "adopter" state is somewhat limited.

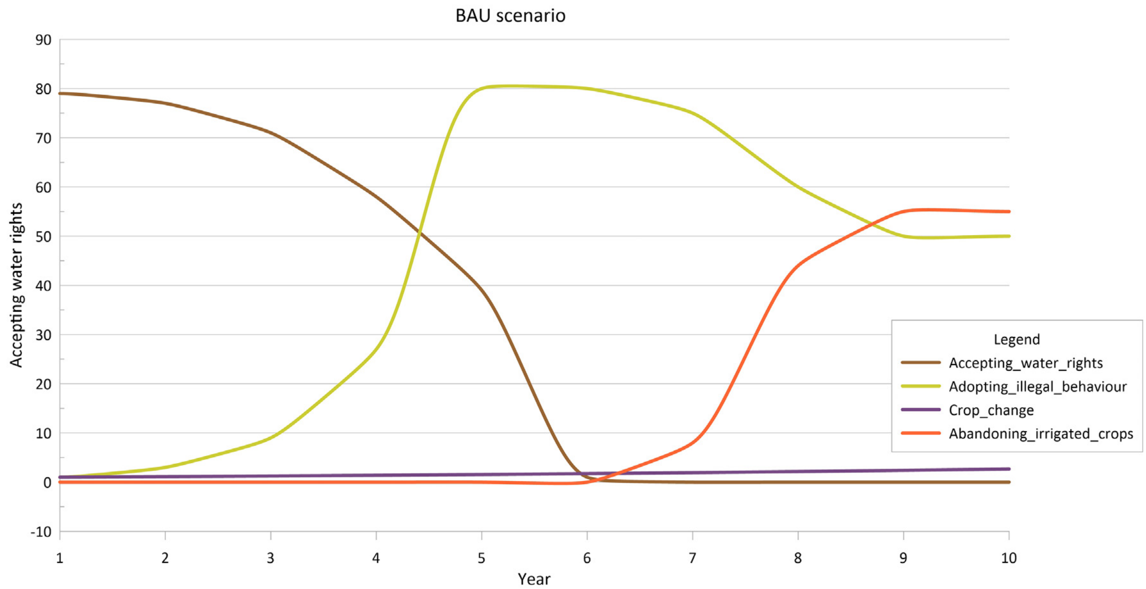

Fig. 7. Simulation of the BAU scenario. The x-axis represents the years of the simulation. The y-axis the number of farmers adopting a specific behaviour.

The fuzzy inference was used to combine CHD reputation and territory control and define the farmers' attitude toward illegal behaviour. In case of low CHD reputation and a perceived lack of territory control, farmers decide to adopt illegal behaviour and exploit GW resources, disrespecting the CHD decision. In the short term, this strategy allowed farmers to achieve a satisfactory level of production. The number of farmers adopting illegal behaviour is high in the aftermath of the drought onset. However, this strategy affects the GW state due to the low GW recharge. The GW availability decreases in the medium and long terms, forcing farmers to abandon the irrigated crops. This has an impact on the economic sustainability of the farms. Fig. 7 shows the results of the model simulation in the BAU scenario.

The analysis of these results allows us to assess to what extent the vulnerabilities in the network of interactions could affect the NBS implementation. The BAU scenario is characterised by a rather low level of social attitude in the farmers' community. The lack of WUA impedes the increase of this parameter and, consequently, the spread of the innovation concerning the crop change due to technical support (one of the selected NBS). Moreover, the low initial value of the CHD reputation does not increase during the simulation because of the limited capability of the CHD to share GW information with farmers. Similarly, the low level of acceptance of the water rights does not increase during the simulation because of the low CHD reputation. In these conditions, the implementation of the managed aquifer recharge - i.e. the second selected NBS - would be hampered by the farmers' behaviour, which is still oriented toward the unsustainable exploitation of the GW for irrigation purposes.

3.3. Co-defining networking interventions

The results of the hybrid ABM-SDM simulation of the BAU scenario were used for informing the stakeholders' engagement in defining the networking interventions. A second workshop was organised in the study area, involving institutional actors, farmers, representatives of farmers' association and local citizens. Participants were requested to identify potential actions for overcoming the detected vulnerabilities in the network of interactions.

At the beginning of the workshops, participants agreed to merge two of the detected vulnerabilities, i.e. the WUA formation and water rights management. According to participants' opinions, the connection between these elements was too tight to separate discussion. Therefore, participants were divided into 3 small groups, composed of maximum 10 stakeholders. Each group focused on one of the identified vulnerabilities.

Participants were requested to identify networking interventions - i.e. introduction of information, tasks and actors in the network of interactions - capable of addressing the identified vulnerabilities. Three intervention strategies, combining different networking interventions, were co-defined, as shown in Table 9.

The hybrid ABM-SDM was used to simulate different interventions scenarios and assess the networking strategies' effectiveness. Concerning ST.1, the enhancement of the territory control reduces the farmers' propensity to adopt illegal behaviour in case of enforcement of GW use limitations due to CHD decision. In the short term, thus, ST.1 provokes a reduction of GW exploitation but also a reduction of crop strategy effectiveness. However, the high acceptability of the water rights - because of the increased transparency of the water rights assignment process - leads farmers to enter the WUA and, consequently, increase their social capital. Therefore, the number of farmers adopting a social attitude increases and farmers do not act as individual agents anymore. The number of farmers looking at the other community members to get hints about innovations in cropping strategy slightly increases because of the increase of the farmers' social capital and social attitude. Innovations start spreading in the farmers' community because of the effectiveness of the "word-of-mouth" sharing mechanisms. Therefore, in the medium and long-term, ST.1 becomes economically sustainable for the farmers due to the adoption of less water demanding crops that allow farmers to reduce the GW exploitation and keep the land cultivated.

Table 9
Networking interventions as defined by the stakeholders.

Strategy	Vulnerability addressed	Networking intervention
ST.1	WUA formation and water rights management	Control of the territory Transparency of water right process
ST.2	GW state information	GW control investment (GW metering) GW state information GW extraction costs
ST.3	Technical support to farmers for crop change	Drought resistant crops Market evaluation support Training and capacity building

ST.2 aims to enhance the CHD knowledge about the actual state of the GW through investment in GW metering and control and share this information with the farmers. As described in the previous section, the effective sharing of this information increases the CHD reputation and, consequently, the acceptance of water rights. However, the process for enhancing the water rights' acceptance is slower than in ST.1, since there is no direct action pursuing this goal. The WUA formation process, which is influenced by the water rights' acceptance is slower as well. Therefore, in the short term, ST.1 is more effective than ST.2. However, in this scenario, CHD can enhance the understanding of the GW state and, thus, improve the management of water rights. This, in turn, has a positive impact on the farmers' perception of the CHD role and, consequently, leads to a higher acceptance of the water rights management process. The reinforcing loop between water rights acceptance and WUA formation leads to a higher number of famers adopting crop change and, thus, reducing GW exploitation. Therefore, in the medium and long term, ST.2 is more effective than ST.1.

Finally, ST.3 aims at providing technical support to farmers to enable the crop change. This strategy is quite effective in the short term. However, as described in Section 2, the low level of trust and the lack of WUA formation process hampers the effectiveness of this intervention strategy in the medium and long terms. The lack of social capital in the farmers' community reduces the effectiveness of the innovation adoption. Moreover, the perceived lack of control of the territory leads some farmers to act illegally and increase GW exploitation.

Fig. 8 shows the results of the model simulations for the three intervention scenarios.

Comparing the simulated impacts of the different intervention strategies allowed us to indicate ST.2 as the most effective network intervention strategy for overcoming collaborative barriers and enabling NBS implementation in the Medina del Campo demo site.

4. Discussion

This section is meant to discuss the main results of the activities carried out in Medina del Campo and demonstrate the adopted methodology's suitability in providing answers to the key research questions mentioned in the introductory section. Moreover, this section discusses the pros and cons of the adopted approach compared to the existing literature.

4.1. Network of interaction and NBS implementation

Several works are mentioned in the scientific literature dedicated to detecting and analysing the main barriers hampering the NBS implementation (e.g. O'Donnell et al., 2017; Ruangpan et al., 2020). Nevertheless, the existing works seem to neglect the role played by the network of interactions among the different decision-agents in enabling/hampering the NBS implementation process. On the one hand, the results obtained in Medina del Campo showed how the social network characteristics in which the decision-agents act and decide could influence the decision-agents' behaviour. Specifically, this work demonstrated that an ineffective interaction network represents a barrier to NBS implementation because it amplifies potential conflicts among the different decision-agents. Lack of information sharing – i.e. limited access to GW state information – might affect the decision taken by the other actors – i.e. the farmers – hampering the implementation of the selected NBS. Moreover, the low level of involvement of potentially key actors, such as the WUA, could prevent key tasks from being performed – i.e., implementing the water right policy and the access to technical support for crop change – and, thus, affect the NBS effectiveness. Finally, the results showed that the key tasks carried out by a single agent, with limited cooperation in the network, represent a vulnerability because it prevents this task from being considered consensual, accepted by the other agents. E.g. the other agents' assignment and management of the water rights was not accepted because it was perceived as not transparent and an exclusive prerogative of the CHD. In line with Matland (1995) findings, this demonstrates that the lack of effective interactions could hamper the definition of actions for enabling the transition from conflicts toward cooperation among agents with ambiguous problem frames.

On the other hand, the results in Medina del Campo demonstrate that overcoming the barriers to collaboration through the networking interventions, could have positive impacts on the NBS implementation and effectiveness. Therefore, this work indicates that NBS implementation claims to detect and overcome those related to the interaction between the various decision-agents and socio-economic, technical and institutional barriers. Networking interventions prove to be effective in supporting the NBS implementation.

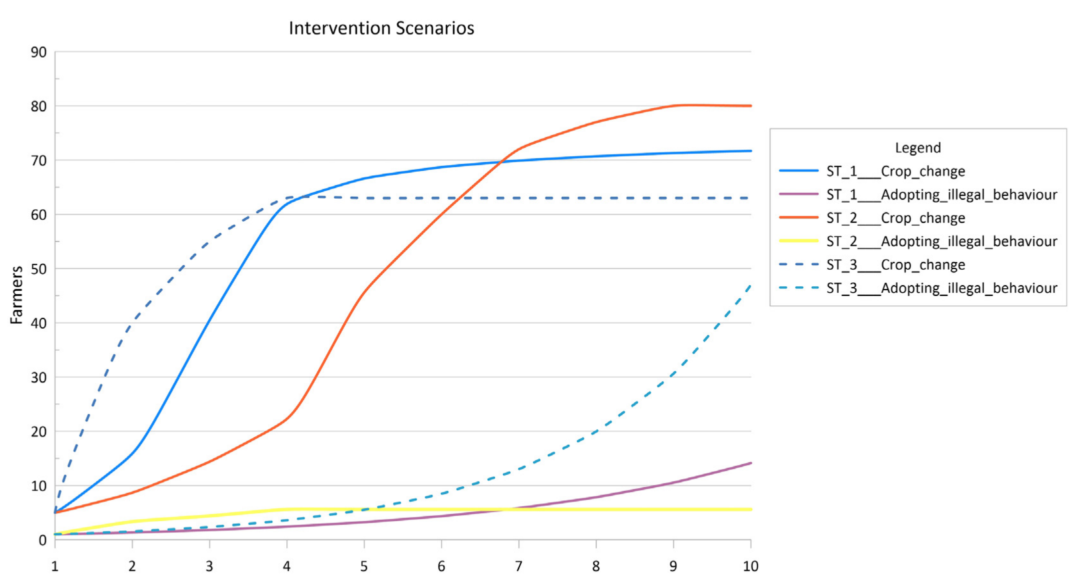

Fig. 8. Comparison among the intervention scenarios effectiveness concerning the implementation of crop change policy (number of farmers adopting it) and reduction of GW exploitation (number of farmers adopting illegal behaviour).

4.2. Methodological innovations

This work brought a methodological innovation concerning implementing the SNA-ABM integrated approach as a tool for detecting the collaboration barriers to NBS implementation and defining the networking interventions. The use of SNA in this domain is not new (e.g. (Calliari et al., 2019a, 2019b; Manson et al., 2016; Therrien et al., 2019). Nevertheless, in many cases, the network analysis is limited to mapping the social network – i.e. the interactions among different agents – and using metrics for describing the structure of the network. Therrien et al. (2019) suggested characterising the connections among the actors accounting for three main elements, that is, type of connections (collaboration, funding, etc.), strength and quality (openness, competition, history, etc.). Calliari et al. (2019a, 2019b) describe a mixed-method approach based on integrating quantitative and qualitative SNA. In line with these efforts, the results obtained in this work demonstrate that the effectiveness of cooperation among different decision-agents depends on interplaying factors – i.e. actors, knowledge and tasks. Therefore, this work showed that the detection of collaborative barriers to NBS implementation requires extending the analysis of the interactions among agents, enhancing the understanding of how the information flows through the network of interactions, and how the shared information allowed the involved actors to cooperate in carrying out key tasks in the process. To this aim, the combination of different graph theory measures demonstrated to detect the key vulnerabilities in the network of interactions effectively.

Our experiences demonstrate that, although innovative, the SNA approach does not provide enough information for defining the networking interventions. SNA is a powerful tool for detecting the key nodes – i.e. entry points of interventions (e.g. Giordano et al., 2017a, 2017b; Calliari et al., 2019a, 2019b). The integrated implementation with the hybrid ABM-SDM allowed us to overcome these drawbacks. The integrated SNA-ABM method allowed us: i) to unravel the complex network of interactions taking place between the various decision-agents; ii) to detect the key vulnerabilities in the network; iii) to analyse the causal connections leading to the detected vulnerabilities in the network; iv) and to explain how those interaction vulnerabilities affect the decision-agents' behaviour, contributing to hamper the NBS implementation. This represents an innovation in the way SNA and ABM are combined. As discussed in (Will et al., 2020), the combination between SNA and ABM aims mainly either at investigating the mechanisms of diffusion within a community of agents or to model the social integration of agents into a community. Our work aims to make a step forward by using the SNA-ABM combination to detect the key vulnerabilities in the network of interactions and analyse how the lack of effective interaction could influence the agents' behaviour and decision-making processes. To this aim, our efforts were greatly facilitated by the work of (Schlüter et al., 2017). The theories of behavioural decision-making cited in (Schlüter et al., 2017) allowed us to formalise the agents' behaviours and, thus, to create a model as close as possible to the actual behaviour. The use of behavioural theories and fuzzy linguistic functions facilitated the interaction with the stakeholders. The developed hybrid ABM-SDM describes agents' behaviours accounting for the actual agents' reasoning and uses familiar terms to farmers. Therefore, the model's results were relatively simple to be understood by non-experts. The model comprehensibility for the participants increases its legitimacy in the decision-making context. Thus, stakeholders were facilitated in participating in the discussion for the definition of the networking interventions. Moreover, the ABM was based on the knowledge collected through the interaction with the stakeholders. Therefore, participants could recognise their contributions in the model, developing a sense of ownership toward it and the obtained results.

4.3. The time dimension in NBS implementation

Another important innovation demonstrated by the obtained results concerns the necessity to introduce the time dimension in the definition of the networking interventions. As shown in Section 3, the interventions' impacts may occur at different time steps. Some of the selected interventions have substantial impacts in the short term, that could be diluted in the medium and long term. Other interventions may have limited impacts in the short terms – i.e. those aiming at fostering behavioural changes – but are characterised by strong and durable impacts in the long-terms. Neglecting the time scale of these processes could lead to an erroneous and over-simplified selection of networking interventions. The dynamic nature of the hybrid ABM-SDM demonstrated to be suitable in making decision-agents capable of accounting for the time dimension in assessing interventions' effectiveness.

4.4. Main limits of the adopted methodology

The main drawbacks of the adopted methodology are described here. The main limitation concerns the analysts' biases in several phases of the described methods (LaMere et al., 2020). Firstly, during the development of the map of interaction to be used for the SNA. The adopted approach is a semi-quantitative one. Contrary to the quantitative approach, based on the numbers of contacts between different agents, the proposed approach refers to the stakeholders' judgements concerning the importance of the different connections in the map. Therefore, the analysts are required to translate a qualitative statement into a number for the SNA model. This could represent a drawback. Secondly, the simulation of the agents' decision-making is based on a fuzzy inference engine. To this aim, fuzzy linguistic functions were used in this work, requiring us to interact with the stakeholders to build the fuzzy functions (Page et al., 2012), which could impact stakeholders' fatigue. This is a key issue to be addressed when defining the plan of the stakeholders' engagement activities. Thirdly, during the development of the individual behavioural model, analysts may introduce biases in the attempt to reproduce stakeholders' behaviour from the interviews (LaMere et al., 2020). The interview framework was structured to lead stakeholders to be explicit about the conditions influencing the selection of the adequate actions for pursuing their objectives. Moreover, as already stated, the reference to the behavioural decision-making theories allowed us to formalise the agents' behaviour reducing the analysts' biases.

Finally, due to time constraints in the third workshop, we were forced to split the participants in three groups, each focused on a specific issue. This negatively impacted the richness of the collected knowledge.

5. Concluding remarks

Enabling NBS implementation and enhancing their effectiveness in reducing climate-related risks requires shifting the focus from technical barriers to socio-economic domains. In line with these works, the experience carried out in Medina del Campo aimed at enabling the NBS implementation by overcoming the collaboration barriers. By conceptualising the NBS as a collaborative decision-making process, this work describes a combination between SNA and hybrid ABM-SDM for encouraging the interactions between the various decision-agents involved/interested in NBS implementation despite the diversity in risk and benefits perceptions, meanings and values. The obtained results showed that, by enhancing the interaction mechanisms, facilitating information flow, and enabling collaboration in performing key tasks, divergent problem frames can still yield collective actions. To this aim, the integrated modelling approach provides decision-agents with useful information concerning: i) the main drawbacks (vulnerabilities) of the existing network of interactions; ii) the entry points for the interventions – i.e. the actors to be interested by the networking interventions; the information to be shared; and the tasks to be carried out in cooperation with the others; and iii) the most suitable interventions to be implemented.

CRediT authorship contribution statement

R. Giordano: Conceptualization, Funding acquisition, Formal analysis, Methodology, Software, Validation, Writing – original draft, Writing – review & editing. **M. Manez-Costa:** Formal analysis, Supervision, Conceptualization, Writing – original draft, Writing – review & editing. **A. Pagano:** Formal analysis, Supervision. **B. Mayor Rodriguez:** Formal analysis, Supervision, Validation. **P. Zorrilla-Miras:** Formal analysis, Supervision, Validation. **E. Gomez:** Formal analysis, Supervision. **E. Lopez-Gunn:** Conceptualization, Funding acquisition, Project administration, Supervision, Validation.

Declaration of competing interest

The authors declare to have no conflicts of interests.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.149734.

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