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Causal Loop Diagrams for supporting Nature Based Solutions participatory design and performance assessment

Virginia Rosa Coletta [a,b,*], Alessandro Pagano [b], Irene Pluchinotta [c], Umberto Fratino [a], Albert Scrieciu [d], Florentina Nanu [e], Raffaele Giordano [b]

[a] *DICATECh, Politecnico di Bari, Bari, Italy*
[b] *Water Research Institute - National Research Council (IRSA-CNR), Bari, Italy*
[c] *Institute for Environmental Design and Engineering, The Bartlett Faculty of the Built Environment, University College London, UK*
[d] *National Institute of Marine Geology and Geoecology (GeoEcoMar), Bucarest, Romania*
[e] *Business Development Group (BDG), Bucarest, Romania*

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ABSTRACT

The contribution of Nature Based Solutions (NBSs) for supporting climate change adaptation and water-related risks reduction is becoming increasingly relevant for policy and decision-makers, compared to 'grey infrastructures', thanks to their capability to jointly deal with a multiplicity of societal and environmental challenges, producing several co-benefits besides limiting the impacts of water-related risks. Nevertheless, their mainstreaming is still limited by several barriers, which are often related to socio-institutional (e.g. limited cooperation and stakeholders' involvement, limited awareness about NBSs impacts) rather than to technical aspects. In this context, innovative tools for NBSs planning, design, implementation and assessment are required, along with effective processes capable of supporting stakeholders' participation. The present research aims to propose a shift in the approach to NBSs design, based on the early stakeholders' involvement in the identification, modelling and performance assessment in terms of benefits and, particularly, co-benefits production. A multi-step methodology was implemented for the purpose, combining both individual and participatory activities. Reference is made to one of the case studies of the NAIAD project, namely the Balta Potelu Pond Area (Lower Danube, Romania). Causal Loop Diagrams (CLDs) were used to describe the system in terms of causal connections and mutual influences, incorporating stakeholders' views and ideas. Inputs from both institutional (e.g. ministries and municipalities) and non-institutional stakeholders (e.g. NGOs and members of the local communities) were integrated. This allowed a comparative assessment of multiple NBSs, based on the analysis of benefits and co-benefits produced, as well as the identification of trade-offs among different stakeholders (e.g. the increase of agricultural production versus biodiversity conservation) and potential side effects. CLDs were then coupled with a Performance Matrix (a basic feature of Multi-Criteria Decision Analysis) and fuzzy logic to help decision-makers identify the most suitable NBSs for the area. The whole process was aimed at facilitating the process of NBSs selection and analysis, while considering the multiple impacts associated with their implementation.

1. Introduction

Natural disasters, and particularly water-related risks (floods and droughts), are increasing in both frequency and magnitude, showing severe effects on communities, on the economy, and on the built environment (UNISDR, 2015). The impacts of these events are even worsened by additional pressures such as climate change, increasing urbanization, and land-use changes (Faivre et al., 2017). An increasing prominence across EU policies is being attributed to the 'working with nature' method (Kabisch et al., 2017), and Nature Based Solutions (NBSs) are becoming central in responding to challenges through innovative actions that are either inspired or supported by nature (EC, 2015). Their increasing popularity is related to a capability of simultaneously providing multiple environmental, social and economic benefits, and a systemic perspective oriented to the climate change adaptation, sustainable management, conservation and restoration of

* Corresponding author. DICATECh, Politecnico di Bari, Bari, Italy.
E-mail address: virginiarosa.coletta@poliba.it (V.R. Coletta).

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ecosystems, sustainable and economic growth (Maes and Jacobs, 2015; Raymond et al., 2017; Alves et al., 2019). These 'co-benefits' represent the value added associated to their introduction instead of (or along with) grey infrastructures (Albert et al., 2019).

Although evidence has demonstrated that co-benefits may represent the main driver for NBSs implementation (Larson and Perrings, 2013; McVittie et al., 2018), most of the methods for operationalizing NBSs design and implementation introduce the co-benefits definition at the end of the process, aiming at contributing to an *ex-post* assessment of NBSs effectiveness (Raymond et al., 2017; Ruangpan et al., 2020). Only a few works have proposed frameworks for NBSs selection and design explicitly starting from the co-benefits analysis (see e.g. Alves et al., 2018).

Murti et al. (2019), Ruangpan et al. (2020), and Giordano et al. (2020) demonstrated the role of active stakeholders' involvement in NBSs design for increasing social acceptance of these solutions (Wihlborg et al., 2019; Pagano et al., 2019). In line with these works, this research aims at proposing an innovative approach for NBSs design and operationalization (i.e. selection, evaluation, and analysis), based on the active stakeholders' engagement for co-benefits definition and assessment since the early phases of NBSs co-design, and grounded in analytical methods for the detection of trade-offs. This allows for a clear identification of the potential multi-dimensional impacts and side-effects of potential NBSs implementation, thus supporting in the identification of the most suitable one(s) in view of the strategic objectives selected for the area under investigation. For this purpose, an innovative methodology based on the integration between Causal Loop Diagrams (CLDs) and Multi-Criteria Decision Analysis is adopted. This work aims at providing answers to the following research questions: i) to what extent does the implemented methodology improve stakeholders' understanding about the system and provide an insight into the complex network of cause-effect chains related to the production of benefits and co-benefits?; ii) is the stakeholders' engagement process capable of boosting stakeholders' learning processes about the mutual influences among co-benefits productions and potential trade-offs among different beneficiaries?; iii) is the adopted modelling approach capable of describing the multi-dimensional effects of NBSs on the system under investigation, explicitly integrating local knowledge? The methodology, developed within the EU funded project NAIAD, is hereby described with specific reference to the Lower Danube case study (Romania).

2. Participatory system dynamics to support NBSs design

Ruangpan et al. (2020) highlighted that the multidimensionality of co-benefits production is the main added value of NBSs compared to grey infrastructures. In this regard, significant advances have been made also to build interdisciplinary frameworks for NBSs assessment in terms of co-benefits production (see e.g. Raymond et al., 2017; Alves et al., 2018; Lanzas et al., 2019; Pagano et al., 2019). However, there are still several knowledge gaps (see e.g. Frantzeskaki et al., 2017; Debele et al., 2019; Ruangpan et al., 2020), such as mainly: i) the partial inclusion of local stakeholders in frameworks and models throughout the process, and ii) the limited capability to thoroughly describe the multi-dimensionality of NBSs, due to an oversimplification of the complex network of cause-effect relationships and mutual influences among co-benefits (Narayan et al., 2017; Lanzas et al., 2019).

There is some evidence that NBSs may even produce negative effects (dis-benefits or co-costs) (Alves et al., 2019; Calliari et al., 2019) as well as trade-offs, related to how differently stakeholders perceive and evaluate co-benefits (Shresta and Dhakal, 2019; Giordano et al., 2020). The limited stakeholders' involvement throughout the process of NBSs design and implementation is directly responsible for an uneven distribution of the co-benefits' fruition among the different potential beneficiaries (Jacobs et al., 2016). Stakeholders' engagement has a crucial role to support understanding and valuing the differences among individual co-benefits (e.g. Small et al., 2017; Giordano et al., 2020). Neglecting such differences and the potential effects of trade-offs, may condition the capability to effectively design NBSs (e.g. Raymond et al., 2017; Alves et al., 2019), and also potentially lead to conflict and barriers to a successful NBSs implementation (e.g. Giordano et al., 2017; Shrestha and Dhakal, 2019).

Participatory System Dynamic Modelling (SDM) approaches have the potential to overcome such limits, due to their ability to account for the complex, non-linear interactions among the different elements affecting NBSs design and implementation, and to facilitate the integration between scientific and stakeholders' knowledge. This has been demonstrated by several recent works (see e.g. de Vito et al., 2017; Zomorodian et al., 2018; Santoro et al., 2019; Pagano et al., 2019). Among the different methods for participatory SDM, the present work uses CLDs as a tool for supporting a collective system understanding and modelling (see e.g. Mirchi et al., 2012; Inam et al., 2015; Giordano et al., 2019; Perrone et al., 2019 for further details). The use of CLDs mainly helps to describe the complex set of interconnections and loops affecting the system dynamic evolution, before and after the introduction of NBSs, thus allowing for the identification of the main mechanisms that contribute to the production of the expected co-benefits and to the generation of trade-offs between the stakeholders. Compared to other SDM approaches, CLDs were selected also for their capability to map and visualize the network of interactions among the different system components, making it understandable for non-expert people and, therefore, facilitating the discussion among stakeholders and between them and the local experts (Inam et al., 2015).

3. Description of the methodology

3.1. Overview of the approach

The approach described in the present section is a participatory multi-step methodology designed and applied with a threefold objective: firstly, to identify and rank (through both individual and group exercises) the most relevant strategic objectives for the study area (i.e. the benefits and co-benefits that should be produced by NBSs); secondly, to build (integrating expert and scientific knowledge) a CLD representing the causal influences among the main variables and the potential effects of the introduction of a set of NBSs; thirdly, to support the design phase based on the comparative analysis of NBSs with respect to the selected strategic objectives for the area. The methodological framework is represented in Fig. 1 and described in full details in the following. It is consistent with the NAIAD Stakeholder Engagement Protocol, which has been implemented in several different case studies, and all activities involving stakeholders comply with both the Data Management Plan and the ethical principles concerning social research activities defined within the project.

The first step is based on semi-structured interviews with relevant local stakeholders, to enhance the richness, diversity and complexity of available knowledge. The framework for the interviews is structured in order to elicit stakeholders' understandings both of the main water-related risks to be dealt with, and of the multiple objectives to be achieved through the NBSs implementation (i.e. different benefits and co-benefits to be produced) (Bain et al., 2016). The information derived from the semi-structured interviews are then processed and Individual Fuzzy Cognitive Maps (FCMs) are built in order to represent stakeholders' conceptual model on the system under consideration (e.g. Mehryar et al., 2019; Pluchinotta et al., 2019; Santoro et al., 2019). Afterwards, the individual FCMs are analyzed in order to infer stakeholders' objectives, using the Centrality Degree analysis, performed by evaluating the complexity of the surrounding causal chains in Individual FCMs (Ackermann and Alexander, 2016). This supports the detection of the key elements according to the stakeholders' risk perception (Eden, 1992), i.e. the set of potential co-benefits.

The second step, based on group activities performed during the first stakeholder workshop, is oriented to collaboratively discuss the subset

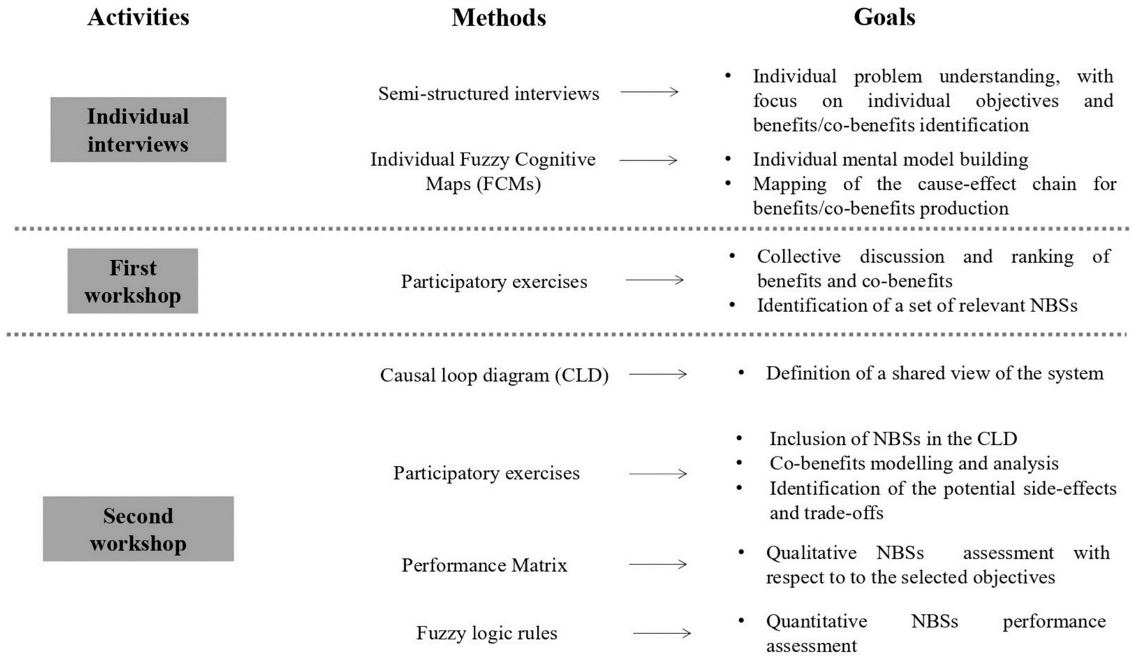


Fig. 1. Scheme of the methodological approach.

of co-benefits, and to reach consensus in their ranking through participatory exercises. Afterwards, the stakeholders are also asked, in a group discussion, to identify a set of suitable NBSs for the study area. After being given a NBSs catalogue, participants are asked to select the NBSs they consider more suitable for dealing with local water-related risks while positively contributing to the production of the high-ranked co-benefits.

The third step, based on group activities performed during the second stakeholder workshop, is oriented to build a shared vision of the system under investigation through the definition of a CLD. The developed CLD specifically aims to identify the main cause-effect chains affecting the dynamic evolution of the system (Jeong and Adamowski, 2016) with a focus on the production of the high-ranked benefits and co-benefits. This is useful to provide a qualitative description of the state of the system in the current condition, i.e. without the implementation of any measure, as well as in the case of the introduction of the selected NBSs. A qualitative analysis of feedback loops is thus coupled with a quantitative tool, i.e. a Performance Matrix, for the purpose. Full details on this step are in the following Subsection 3.2.

3.2. CLDs and Performance Matrix to support NBSs co-design

The developed CLD provides a straightforward graphical representation of the system under investigation, focused on the relationships among different variables, including benefits, co-benefits, and any other influential element on system behavior. The strength of connections between variables is modeled through weights and shown through different thicknesses and colors. Delays relative to the time horizon of the connection can also be used (a symbol // is put on the arrow). The direction of the connections between such variables defines the causal dependency, being positive (+) if the variables change in the same direction (i.e. they both increase or decrease) or negative (−) if they change in the opposite direction (Sterman, 2000). Combinations of positive and negative causal relationships can form either reinforcing (‘R’) and balancing (‘B’) feedback loops. Reinforcing loops represent growing or declining actions, while balancing loops represent a mechanism of self-correction that contrasts and opposes change, and their analysis is crucial to describe the expected dynamic evolution of variables (Sterman, 2000; Mirchi et al., 2012).

A CLD describing the key dynamics of the study area in current conditions is built first. Afterwards, a group exercise is used to build a revised CLD, in which the main dynamics that can be affected by NBSs introduction are identified. The stakeholders are asked to collectively draw causal connections between the NBSs and the variables present in the CLD, and to identify both a polarity and a weight for each connection. At the end of the process an activity for model validation is also performed. For the purposes of the present work, understanding the main feedback loops in which co-benefits are involved is essential for stakeholders to identify their production mechanisms as well as potential side-effects and trade-offs related to NBSs implementation (Shrestha and Dhakal, 2019).

The qualitative analysis of the feedback loops is then coupled with a quantitative tool, i.e. a Performance Matrix, which is a standard feature of Multi-Criteria Decision Analysis (MCDA, see e.g. Belton and Stewart, 2002). Specifically, a Performance Matrix is a table in which each row identifies an alternative (NBS) and each column describes the performance of the alternative with respect to each criterion (i.e. the selected benefits and co-benefits) (Ferretti and Grosso, 2019). The weight is collectively set and ranges from very good performances (+++, i.e. full achievement of the objective) to very low performances (—, i.e. a potentially negative effect on the selected objective). A 0 is set in case the NBS has no impact on the selected objective.

In order to include stakeholders’ knowledge numerically, fuzzy logic rules are then implemented in the Performance Matrix using MATLAB[1] (see e.g. Giordano and Liersch, 2012). This supports dealing with linguistic variables in a solid mathematical way (Zadeh, 1975), even in situations where information is qualitative, uncertain or incomplete, and a set of rules can describe the relationships among variables (Rajaram and Das, 2010).

Firstly, the selected benefits/co-benefits are set as inputs (usually defined as ‘second-order’ variables). A fuzzy membership function (either triangular or trapezoidal) is then built for each variable, starting from the results of the knowledge elicitation process, which relates the numerical range of the variable to the linguistic values “low”, “medium” and “high”. The same procedure is applied also to the output variables

[1] https://it.mathworks.com/.

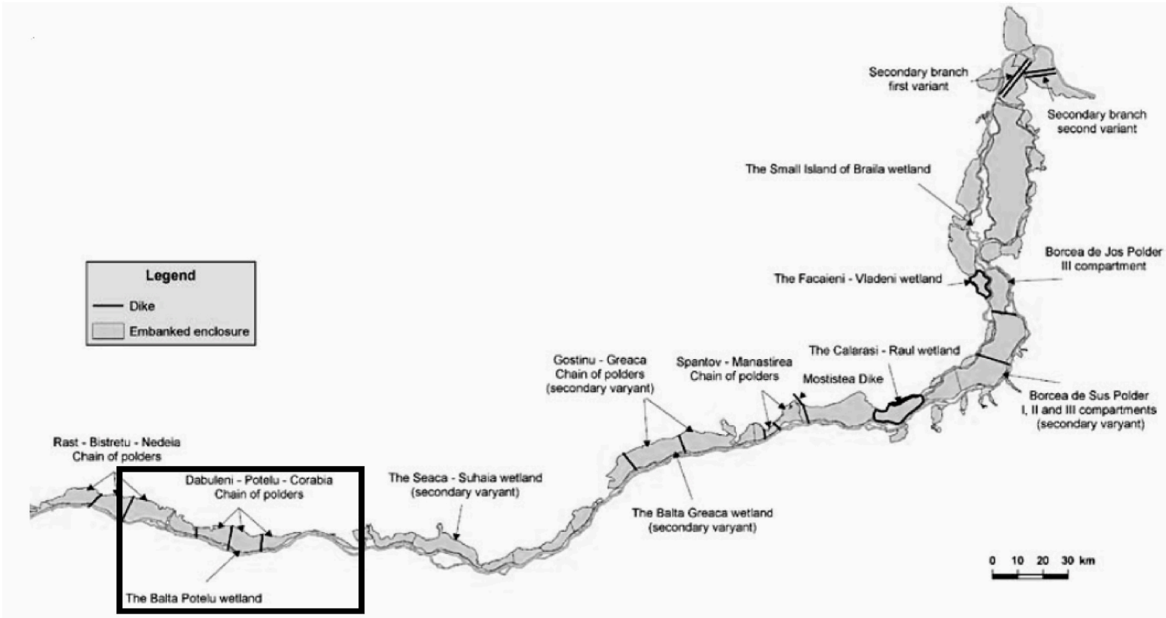


Fig. 2. Overview of the study area (Mihailovici et al., 2006).

(usually defined as 'first-order'), obtained through a process of input variables aggregation (Zimmermann, 1991). Secondly, fuzzy *if … then* rules are created, where the *if*-part of the rule is built with the aggregation of the second-order variables with the "AND" operator, and the *then*-part used to define the corresponding linguistic values of the first-order variables (Uricchio et al., 2004). Lastly, the fuzzy logic rules are used to derive single crisp values, calculated with the Centroid of Area (COA) method (Zimmermann, 1991).

This procedure ultimately allows on the one hand a numerical estimate of the performance of each NBS and, on the other hand, the identification of the most suitable NBS, using a simple weighted average. The results of this analysis are meant to be used as a structured process to draw preliminary recommendations for the decision-makers, taking explicitly into account stakeholders' needs and knowledge.

4. Results

4.1. Overview of the case study

The proposed methodology has been applied to the Lower Danube case study (and particularly, to the Balta Potelu Pond area located between Bechet and Corabia, Romania) (Fig. 2). The area under investigation is a wetland with a well-known ecological and economic potential (see e.g. WWF, 2009; Nichersu and Nichersu, 2015; Tetelea, 2017 for further details). The interest lies mainly in its exposure to the problems arising from climate change and in particular to extreme events (such as floods and droughts), which are amplified due to the progressive intensification of urbanization and of anthropic pressures. Water-related risks are becoming increasingly frequent in the area, showing negative effects on different economic activities (e.g. navigation and agriculture).

Currently the area is mainly devoted to agriculture and the complicated structure of land properties prevents its potential restoration, which would allow a significant water storage during floods. Some studies have started exploring the potential of NBSs in the area, to reduce the impacts of water-related risks, improve ecosystem services, protect biodiversity, but the process is hampered by the limited local and national support and by the resistance by communities. For such reasons, the activities of the present study were oriented to guarantee an active participation of stakeholders throughout the process. Full details on the involved stakeholders are included in Table 1 in Supplementary Material.

4.2. Benefits and co-benefits identification and ranking

Three rounds of semi-structured interviews (approximate duration 1 h) with individual stakeholders (or group of stakeholders representing a single institution), one per stakeholder, were held first. The results of this activity (Step 1) showed that the whole area is increasingly affected by persistent droughts and, particularly in some locations, intense floods, both responsible for human and economic losses. Additional issues were also raised individually by the stakeholders, mainly related to the state of the environment and to the economic activities (e.g. agriculture, tourism, etc.), and identified as key elements to support the development of the area. Some problems were also discussed and highlighted by the stakeholders e.g. the negative effects associated to the lack of institutional cooperation and the limited stakeholders' involvement in decision-making.

The first stakeholder workshop (approximate duration 3 h), was held in March 2018 at the headquarters of the River Basin Administration Jiu (Craiova), and oriented to the definition of a ranking among benefits and co-benefits. The main benefits were related to the reduction of the impacts of both floods and droughts, which were considered as equally important. Regarding the main co-benefits for the Balta Potelu wetland, the highest-ranked ones were, in order of relevance: i) the development of eco-tourism; ii) the limitation of migration/depopulation; iii) the increase in biodiversity; iv) the development of fishing and aquaculture activities; v) the increase of agricultural production. Furthermore, the following NBSs were identified as potentially relevant for the area: wetland restoration, retention areas, river renaturation, and reforestation.

4.3. CLD construction - current state of the wetland ecosystem

The second stakeholder workshop was held, with the same stakeholders, in December 2018 (approximate duration 3 h) at the headquarters of the River Basin Administration Jiu (Craiova). A CLD was collectively built (Fig. 3), using the Vensim® simulation software, to describe the current state of the system. The main benefits associated with the reduction of water related risks (i.e. 'drought' and 'flood magnitude') and the selected co-benefits ('biodiversity', 'eco-tourism',

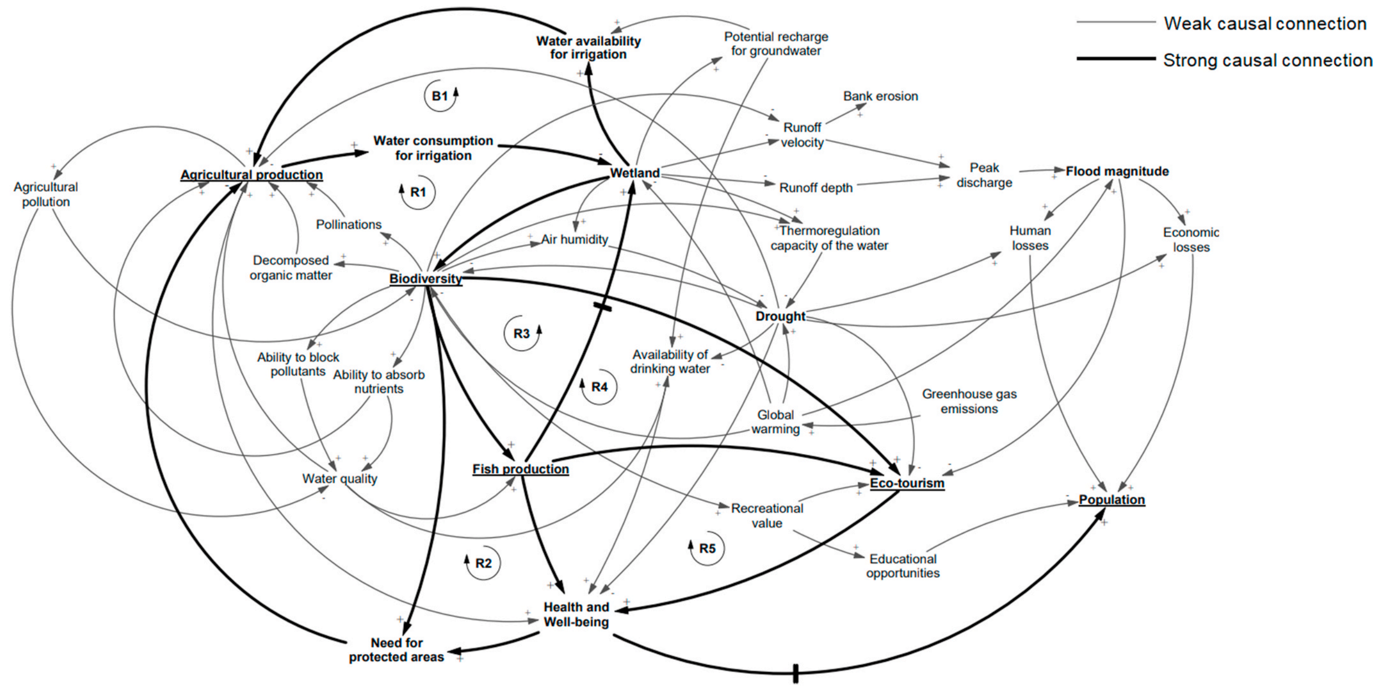


Fig. 3. CLD to describe the dynamics related to the benefits ("drought" and "flood magnitude", in bold) and co-benefits (in bold and underlined) in current conditions in the Balta Potelu wetland area.

'fish production', 'population' and 'agricultural production') are drawn in bold. A thorough description of each variable included in the CLD is proposed in Table 1.

As already mentioned, the analysis of feedback loops (and of their mutual influences) is one of the key features of CLDs. The key feedback loops related to the production of co-benefits are isolated in Fig. 4 and discussed in the following, whereas Table 2 in Supplementary Material includes a comprehensive analysis of the loops with an identification of the variables involved/impacted. The analysis of Fig. 4 highlights that the 'biodiversity' variable is linked to 'agricultural production' (and vice versa) through the R1 reinforcing feedback loop: an increase (or decrease) in the 'wetland' area might generate an increase (or decrease) in 'biodiversity'. This entails a greater (or lower) need to have protected areas available which turns into a respectively lower (or greater) availability of soil for agriculture that conditions the extent of the natural wetland. The R2 reinforcing feedback loop provides other relevant information on the relationship between the 'biodiversity' and 'fish production', which has an impact on 'agricultural production': an increase in 'wetland' areas supports an increase in 'biodiversity', which has an impact on the quality and quantity of the fish and, consequently, on the 'fish production'. This variable is directly related to one of the most relevant productive activities of the area, and thus has a direct influence on human 'health and well-being'. This may result both in a greater 'need for protected areas' that, however, may cause a decrease in 'agricultural production' (due to the limited availability of areas for that purpose) and in an increase, with some temporal delay, of the population.

Furthermore, with specific reference to the interconnection between the 'agricultural production' and 'fish production' variables, some remarks are needed, considering the dynamics described by the B1 and R3 loops. More specifically, the B1 loop shows how the increase in 'wetland' may directly increase the 'water availability for irrigation', with a positive impact on the 'agricultural production'. Nevertheless, this increases the 'water consumption for irrigation', which reduces the water availability related to the wetland, driving this part of the system towards a balance. At the same time, the reinforcing feedback loop (R3) shows that 'wetland' generates an improvement in 'fish production' which, with some temporal delay, will require ever greater wetland areas supporting the activity. Therefore, the B1 loop can lead to a decrease in the 'wetland' areas as an effect of an improvement of 'agricultural production', but this may have a negative impact on 'fish production'. This would require careful consideration at the strategic level, when implementing measures and actions that have an impact on this part of the CLD, since the optimization of the variables 'agricultural production' and 'fish production' is concurrent.

The 'biodiversity' and 'fish production' variables are also separately linked to another fundamental variable, 'eco-tourism': an increase in 'biodiversity' (or in 'fish production') would increase the 'eco-tourism' variable (since both fishing and birdwatching may potentially attract tourists). The link between the variables generates two reinforcing feedback loops (R4 and R5) in the diagram. Both loops show that the increase of 'eco-tourism' due to either an increase of 'biodiversity' or 'fish production', in turn generates a benefit to human 'health and well-being' (which may provide a support for the growth of the local population). This, consequently, generates a greater 'need for protected areas' and may therefore cause a reduction in 'agricultural production'.

4.4. NBSs effectiveness assessment using CLD

The CLD presented in Fig. 3 represents the basis for group activities oriented to describe the effects of the selected NBSs on benefits and co-benefits. A revised version of the CLD is thus built (Fig. 5a), taking into account the multiple NBSs impacts. This is complemented by a Performance Matrix (Fig. 5b), in which the stakeholders provide a qualitative weight to the capability of the NBSs to produce the selected benefits and co-benefits.

Focusing for instance on the 'wetland restoration', it directly increases the wetland area, thus strongly contributing to reduce both the 'flood magnitude' (acting on 'runoff velocity' and 'runoff depth') and the severity of 'drought' (acting directly on 'thermoregulation capacity of water' and 'air humidity'). It thus has a strongly positive effect on the reduction of water-related risks (+++). Furthermore, referring to the reinforcing loops, the 'wetland restoration' has a strongly positive effect on 'biodiversity' (+++) and on 'fish production' (+++). This directly

Table 1
Short description of the variables included in the CLD. The variables in bold represent the benefits, while co-benefits are in bold and underlined.

Variable	Description
Wetland	Ecosystem that is inundated by water, either permanently or seasonally, that derives from the releases from the watercourse and from the rainfall
Runoff velocity	Velocity of surface water, which contributes to the generation of the flood and does not infiltrate in the wetland
Runoff depth	Runoff volume per unit area
Peak discharge	Maximum flow rate in the hydrograph
Flood magnitude	A measure of flood severity
Human losses	Number of deaths due to water-related risks
Economic losses	Costs associated to the impacts of water-related risks
Bank erosion	Removal of soil by water
Potential recharge for groundwater	Water retained within the wet area and potentially contributing to the aquifer
Water availability for irrigation	Volume of groundwater or surface water, which may be used for agriculture
Water consumption for irrigation	Volume of water used for agriculture
Availability of drinking water	Volume of water needed for human activities
Agricultural production	Productivity of the crops
Air humidity	Amount of water vapor contained in the air due to evapotranspiration phenomena
Thermoregulation capacity of the water	Capacity of wet areas to generate a heat exchange which limits the thermal excursion
Drought	Lasting condition of limited rainfall and limited water availability
Recreational value	Leisure opportunities offered by the area (e.g. fishing, bird watching, etc.)
Eco-tourism	Form of responsible tourism related to natural areas
Educational opportunities	Activities, such as environment-related courses, for local people
Greenhouse gas emissions	Release of gases such as methane and carbon in the air
Global warming	Phenomenon of increasing earth temperatures, due to the intensification of the greenhouse effect
Biodiversity	Coexistence, in the same ecosystem, of different animal and plant species that creates a balance thanks to their mutual relations
Fish production	Quantity and quality (size) of fish, produced over a certain period of time per unit area
Ability to absorb nutrients	Nutrients dissolved in water, such as nitrates and phosphates which contribute to soil fertility
Water quality	Measure of the condition of water relative to the main physical and biochemical parameters
Ability to block pollutants	Pollutants from the water are removed through natural assimilation and transformation processes of aquatic vegetation
Decomposed organic matter	Quantity of substance, produced by micro-organisms of fauna and microflora, which is crucial for soil functions and soil quality
Pollinations	Basic mechanism for the seed fertilization and production, contributing to the quality of crops
Agricultural pollution	Release of chemicals and/or micro-organisms in the environmental compartments (air-water-soil) in potentially dangerous concentrations
Need for protected areas	Need for natural areas, with a safeguarded natural, ecological or cultural values, essential for biodiversity conservation
Health and well-being	State of complete physical, mental and social serenity that derives from the satisfaction of the main needs
Population	The total number of people or inhabitants

turns into a strongly positive increase of the 'Eco-tourism' (+++). The 'wetland restoration' also has a direct effect on the increasing 'need for protected areas' (e.g. due to an improved aesthetic value of the site). However, this may cause (according to the R1, R2, R4, and R5 loops) a potential reduction of the variable 'agricultural production' (- -), due to the lack of available land to be devoted to agricultural activities. Lastly, due to the positive effects on most of the connected variables (except on the 'agricultural production'), a significant increase in population (++) would also be expected. A similar analysis was performed for the other NBSs, and the results summarized in Fig. 5b. One of the most interesting findings of this analysis is that the introduction of NBSs might have different effects on different co-benefits, and even generate trade-offs, that should be carefully taken into account by decision-makers. Particularly, for the study area, the model highlights that the selected NBS might negatively impact the 'agricultural production'.

As already mentioned, fuzzy logic rules have then been used for a numerical comparison of the NBSs performance with respect to the selected benefits/co-benefits, which are used as input (or 'second order') variables (see Table 2). Consider, as an example, the variable 'water-related risks', Fig. 6 describes the membership function (ranging between 0 and 1) relating the numerical range of the variable (in this case between 0 and 50%, which represents the increase of flooded areas compared to current conditions) to the linguistic values "low", "medium" and "high". The same procedure was applied to all the second-order variables (see Table 2). Output variables were obtained by the aggregation of input variables. Specifically, the 'environmental performance' was obtained by aggregating 'biodiversity', 'agricultural production' and 'fish production', while the variables 'socio-economic performance' and 'hydraulic performance' aggregating 'ecotourism and population' and 'water-related risks' respectively. Regarding the fuzzy *if … then* rules creation, the following lines include an example, referring to the output variable 'environmental performance'.

1. IF biodiversity is high AND agriculture is high AND fish is high THEN environmental performance is high.
2. IF biodiversity is high AND agriculture is medium AND fish is medium THEN environmental performance is high.
3. IF biodiversity is high AND agriculture is low AND fish is low THEN environmental performance is high.
4. IF biodiversity is high AND agriculture is medium AND fish is high THEN environmental performance is high.
5. IF biodiversity is high AND agriculture is high AND fish is low THEN environmental performance is high.
6. IF biodiversity is high AND agriculture is medium AND fish is high THEN environmental performance is high.

Reflecting on the Performance Matrix in Fig. 5b, the fuzzy logic rules were used to derive single crisp values defining the environmental, socio-economic and hydraulic performance for each NBS (see Table 2). The 'wetland restoration' is thus selected as the most suitable NBS, with a weighted average of 68.9. This is mainly due to the highest value of the socio-economic performance, together with the 'river renaturation' (which however has lower values for the other performances). This ultimately reflects the importance of ecotourism, a key variable for socio-economic performance, which was considered by stakeholders as the most important co-benefit.

5. Discussion

This section discusses to what extent the activities described in this work allowed us to respond to the three main research questions mentioned in the introduction.

Concerning the first point, it is worth noticing that the proposed sequence of individual and participatory activities allows moving from individual perspectives, focused on the identification of personal objectives and priorities, to the definition of a shared conceptual view of the system under investigation and of the most relevant objectives to achieve, directly including the knowledge provided by the stakeholders. The integration with technical knowledge enriches the CLDs, which can provide a comprehensive and understandable view of the system under investigation, both in current conditions and after NBSs introduction. Compared to other modelling methods for dynamic analysis (e.g. Stock-and-flow), CLD demonstrated great potentialities in facilitating the interaction with the stakeholders. CLD did not force the analysts to

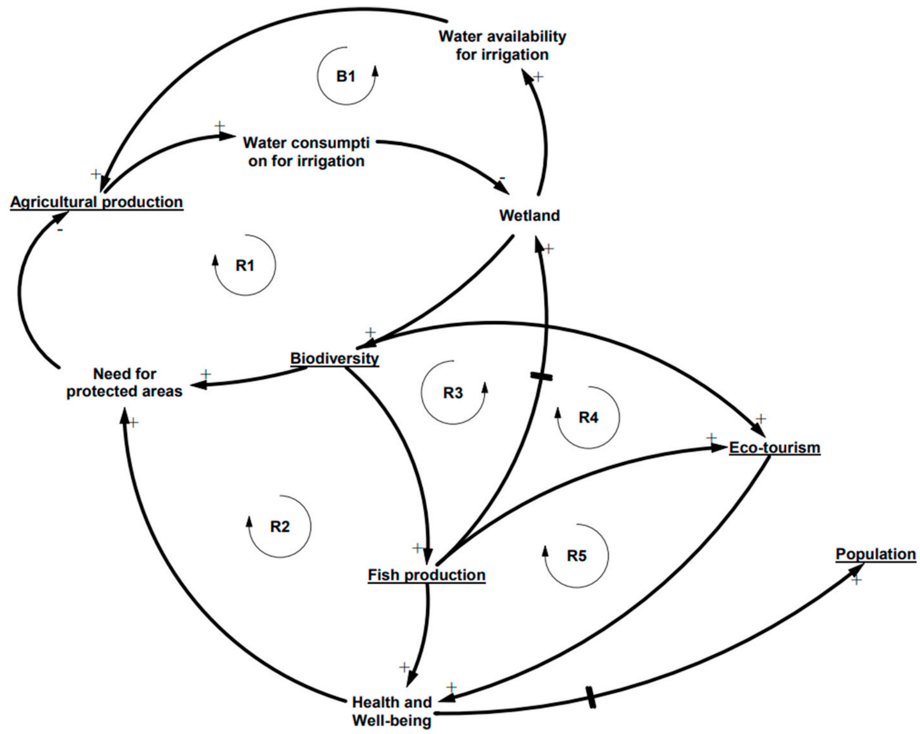
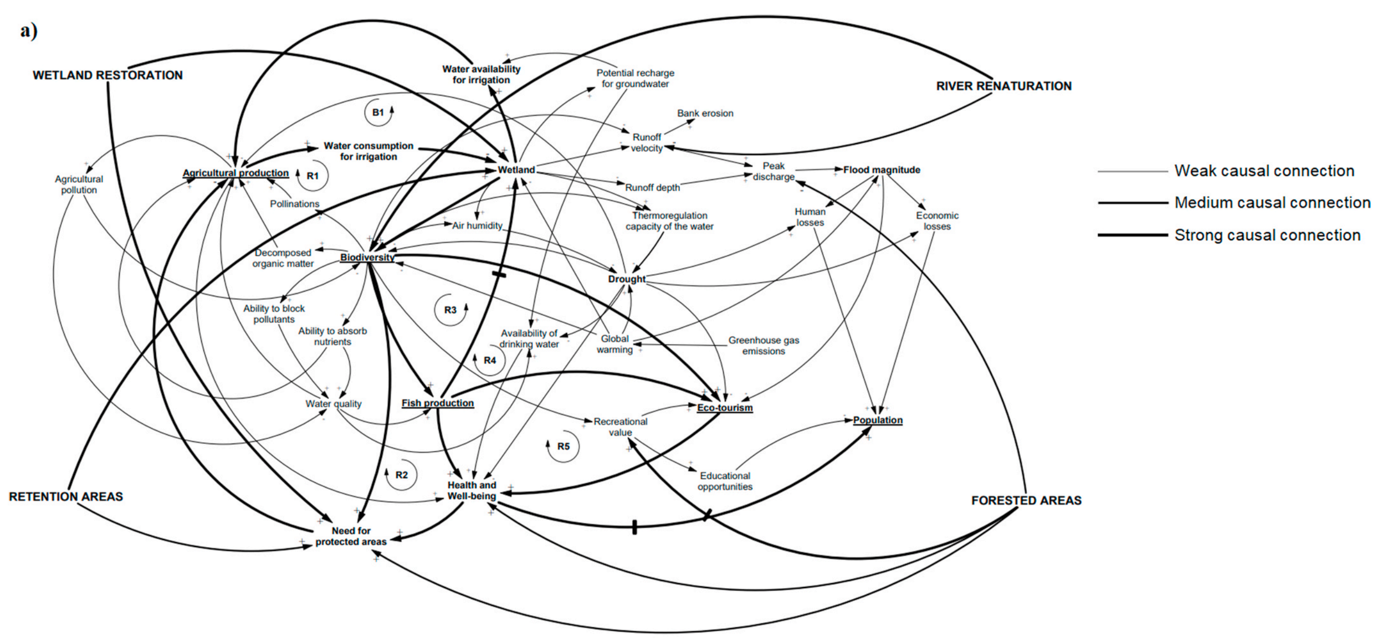


Fig. 4. Main feedback loops, discussed with local stakeholders, on the benefits and co-benefits of the Balta Potelu wetland.

a)



b)

Alternatives/NBSs	Objectives/Benefits and co-benefits					
	Water-related risks reduction	Biodiversity increase	Agricultural production increase	Eco-tourism increase	Fish production increase	Population growth
Wetland restoration	+++	+++	- -	+++	+++	++
River renaturation	+	++	0	++	+	++
Retention areas	+++	+	-	+	++	+
Forested areas	+	++	- -	+++	+	+

Fig. 5. a) CLD including the effects of the selected NBSs, **b)** Performance matrix.

Table 2
Variables considered in fuzzy procedure. The numerical values of the input variables are obtained on the basis of the symbols of the Performance Matrix in Fig. 5, while those of the output variables represent the centroid of the area of each fuzzy membership function. The values are related to the selected NBSs (i.e. wetland restoration, river renaturation, retention areas, forested areas).

	Variable	Numerical range	Numerical value			
			Wetland Restoration	River Renaturation	Retention Areas	Forested Areas
INPUT	Water-related risks	0-50 (variation of flooded areas compared to current conditions [%])	3	10	3	10
	Biodiversity	0-100 (number of animal and plant species in the area)	90	32	42	32
	Agricultural production	0-60 (tons per hectare of the main crops of the area in a year)	12	24	20	12
	Eco-tourism	0–35.000 (expected annual average number of tourists in the area)	3.2e+04	2.7e+04	1.6e+04	3.2e+04
	Fish production	0-50 (variation of fish nursery areas compared to current conditions [%])	45	20	30	20
	Population	0–500.000 (annual average number of people living in the area)	3.5e+05	3.5e+05	2.5e+05	2.5e+05
OUTPUT	Environmental performance	0-100 (variation compared to current conditions [%])	68.9	67.7	51.7	67.7
	Socio-economic performance	0-100 (variation compared to current conditions [%])	68.9	68.9	46.6	67.1
	Hydraulic performance	0-100 (variation compared to current conditions [%])	68.9	54.6	68.9	54.6

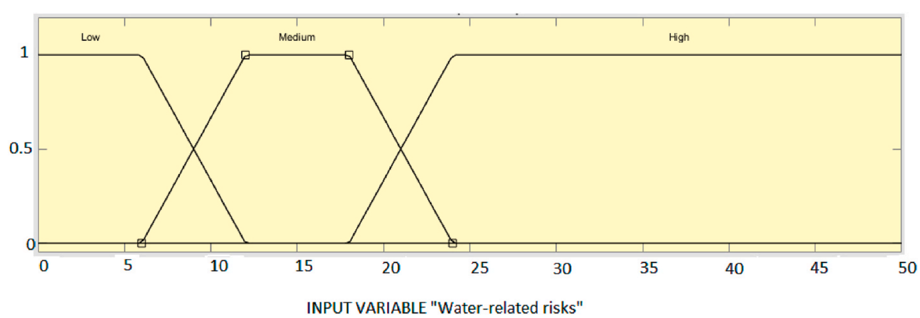


Fig. 6. 'Water-related risks' fuzzy membership function.

translate stakeholders' knowledge and narratives – which are mainly qualitative – into quantitative variables and equations. The CLD model for scenario simulation was built referring to the stakeholders' knowledge elicited during the early phases of project implementation. Therefore, participants were familiar with the causal connections described in the model and were capable of understanding the model. We learned that the adoption of a qualitative modelling approach, such as the CLD, positively affected the interaction with the stakeholders in the different phases of the process' implementation.

Concerning the second research question, compared to most of the existing approaches dealing with the assessment of NBSs co-benefits, the adopted modelling approach allowed for a clear analysis of the dynamics associated with the production of benefits and, particularly, co-benefits, highlighting the interaction mechanisms and the existing and potential trade-offs among co-benefits and between different beneficiaries. This directly contributes to raising awareness about NBSs effectiveness, to increasing social acceptance, and particularly contributes to a more even distribution of the co-benefits' fruition among the various potential beneficiaries.

Concerning the third research question, the use of CLDs compared to static yet comprehensive approaches (e.g. the indicators by Connop et al., 2016; Raymond et al., 2017), gives deeper insight into the potential mutual influences between different co-benefits and the potential trade-offs among them and different beneficiaries. The use of CLDs helps capture the views and ideas of stakeholders within a holistic model structure supporting a continuous exchange of information and knowledge among the participants, which ultimately creates a sense of "ownership" toward the modelling results and the selected strategy. Although CLDs still represent a qualitative tool, the analysis of feedback loops allows for an improved understanding of the multidimensional effects of NBSs implementation (e.g. a potentially negative effect on agricultural production in the study area), which is a key aspect to consider for decision makers particularly in early stages of NBS analysis. The integration with a more quantitative tool, i.e. a Performance Matrix coupled with fuzzy *if … then* rules, obtained from the aggregation of a set of criteria relating to the elements selected by the stakeholders, represents a preliminary attempt to support a structured and comprehensive approach to NBSs design which explicitly takes into account the production of benefits and co-benefits.

Despite the results of the proposed research being promising and clearly highlighting some relevant advantages of the suggested shift forwards in the process of NBSs co-design, some issues need to be carefully considered. In particular, the results are still qualitative or semi-quantitative, and more suitable for supporting strategic planning rather than decision-making and implementation. More quantitative tools would be needed for this purpose, but are beyond the scope of the present work. Research activities are currently already headed in that direction. Furthermore, the proposed model relies on a few hypotheses and simplifications that should be taken into account before implementing the selected measure(s). Just to make an example, in the proposed case study the role market conditions in the 'agricultural production' analysis would have a non-negligible relevance.

6. Conclusions

Starting from the limits of the existing frameworks for NBSs design, the present work proposes a new multi-step methodological approach based on the use of participatory CLDs to feed a simplified MCDA for supporting decisions related to NBSs design.

Through a continuative and active involvement of the most relevant stakeholders, the basic idea is to start from the identification of the most relevant objectives for the case study (benefits and co-benefits), to identify any trade-offs through the building of a shared conceptual view of the system, and to analyze the potential performance of different NBSs. Both individual activities and participatory exercises are included in the framework of analysis, whose main output is a CLD - coupled with a Performance Matrix and fuzzy *if … then* rules - capable of providing a preliminary description of the complex interactions among co-benefits and beneficiaries. Specific reference is made to the Lower Danube case study, one of the NAIAD project case studies.

Credit Author Statement

Virginia Rosa Coletta: Formal analysis, Methodology, Software, Validation, Writing - Original draft preparation, Writing - Reviewing and Editing. **Alessandro Pagano**: Formal analysis, Methodology, Validation, Writing - Original draft preparation, Writing - Reviewing and Editing. **Irene Pluchinotta**: Methodology, Validation, Writing - Original draft preparation. **Umberto Fratino**: Investigation, Supervision, Validation, Visualization. **Albert Scrieciu**: Data curation, Funding acquisition, Project administration, Resources, Writing - Reviewing and Editing. **Florentina Nanu**: Data curation, Funding acquisition, Project administration, Resources, Writing - Reviewing and Editing. **Raffaele Giordano:** Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Validation, Writing - Reviewing and Editing.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2020.111668.

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