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Thinking systemically about climate services: Using archetypes to reveal maladaptation

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ABSTRACT

Developing and implementing climate adaptation measures in complex socio-ecological systems can lead to unintended consequences, especially when those systems are undergoing rapid hydro-climatic and socio-economic change. In these dynamic contexts, a systemic approach can make the difference between adaptive and maladaptive outcomes. This paper focuses on the use of climate services, often touted as no-regret solutions, and their potential to generate maladaptation. We explored the interactions between climate services and adaptation/maladaptation across five case studies affected by different types of natural hazards and characterized by a range of hydro-climatic and socio-economic conditions. Using system archetypes, we show how climate services can play a role in both producing and preventing maladaptation. The dynamics explored through system archetypes are: i) "fixes that fail", where short-sighted solutions fail to address the root causes of a problem; ii) "band aid solutions", where the benefits brought about in the short-term come at the expenses of delaying long-term adaptive actions; and iii) "success to the successful", where some groups increasingly benefit from climate services at the expenses of other groups. We demonstrate how these dynamics constitute maladaptive processes, as well as identifying the tools and theories that can be used in this type of assessment. Finally, we provide a framework and recommendations to guide the ex-ante assessment of maladaptation risk when designing and implementing climate services.

Practical Implications

Climate services have become essential tools for climate adaptation, yet the undesired consequences, or side effects, associated with their applications remain underexplored. This study lays the groundwork for the assessment of the complex link between climate services and their potential to contribute to (mal)adaptive processes. As such, one practical implication of this research is to illustrate archetypes as precautionary tales in the use of climate services with the goal of preventing (or reducing) the risk of unintended consequences.

The study employs system archetypes as a novel tool for ex-ante assessment of maladaptive scenarios arising from the utilization of climate services. Three archetypes – "Fixes that Fail," "Band-Aid Solutions," and "Success to the Successful" – provide valuable insights into how climate services can inadvertently enable unsustainable practices, hinder transformative adaptation, and exacerbate inequalities. The main findings of this research are threefold.

Firstly, the study challenges the prevalent notion that climate services are "no-regret" solutions. By highlighting how immediate benefits from short-term climate services might lead to long-term harm. This challenges the traditional evaluation metrics based solely on user uptake, emphasizing the importance of a comprehensive "uptake-output-outcome-impact" approach.

Secondly, the research advocates for a shift from short-term fixes to a more balanced consideration of long-term adaptation. The identified archetypes demonstrate that while short-term climate

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services may address immediate vulnerabilities, they can perpetuate unsustainable practices and delay transformative measures. This implies that short- and long-term climate services might have competing goals and that for transformative adaptation to reach its full potential, long-term climate services need to be integrated into adaptation strategies.

Thirdly, the study emphasizes the social dimension of climate services, highlighting how climate services can disproportionately benefit certain groups, leading to inequalities. To mitigate this, the research stresses the importance of inclusive co-creation processes that encompass the interests of all stakeholders.

In conclusion, this research contributes significantly to the ongoing development of climate services, emphasizing the link between climate services and maladaptation. Its practical implications consist in identifying tools (i.e. system archetypes) and theories (i.e. the *pathways to maladaptation framework* by Mangan et al (2016)) to guide the ex-ante assessment of maladaptation risk when designing and implementing climate services. Furthermore, we provide a framework to guide the analysis of these interactions in the form of our *conceptualization of the interaction between CSs and adaptation/maladaptation*. This research signals the importance of a comprehensive and inclusive approach, ensuring that climate services not only fulfil immediate needs but contribute genuinely to a sustainable and resilient adaptation.

Introduction

Over the past two decades, climate services (CSs) have emerged as valuable decision-making aids in climate adaptation and other related fields (Hewitt et al., 2012; Hewitt et al., 2020; Hewitt & Stone, 2021; Jacobs & Street, 2020; Lourenço et al., 2016). The expectation is that the use of CSs will contribute to improved adaptive outcomes, as more information leads to better adaptation measures (Kirchhoff et al., 2013; Lemos et al., 2012; Moser, 2014; Naylor et al., 2020; Vulturius et al., 2020). Since the global framework on CSs was introduced in 2012 (C. Hewitt et al., 2012), many international bodies have promoted the development of CSs as a no-regret solution for climate adaptation, meaning that CSs use in decision making in only expected to improve adaptation outcomes, and going as far as stating their usefulness "*for the society at large*" (Jacob et al., 2015).

The pervasiveness of the challenges posed by climate change has indeed spurred many sectors towards developing and adopting CSs tailored to their use cases (Bruno Soares et al., 2018). In particular, agriculture and forestry have both quickly adopted CSs to shore crops from seasonal challenges, hazards, and climatic change (Agovino et al., 2019; Ashley et al., 2020; Hansen et al., 2019; Mason et al., 2022; Solaraju-Murali et al., 2022; Vaughan & Dessai, 2014). The tourist industry uses them to both plan seasonal activities and draw long-term strategies (Font Barnet et al., 2021; Scott et al., 2011). Urban planners use them to aid their decision-making (Lindberg et al., 2018). The disaster risk management field uses CSs to aid in its operations in the development of early warning systems, and in designing preparedness and response strategies (Braman et al., 2013; Jacobs & Street, 2020; Street et al., 2019; UNISDR, 2015; Wilkinson et al., 2018). CSs have also revealed their utility in humanitarian operations, being instrumental in the shift from response towards anticipatory action (Clatworthy, 2022, 2023b, 2023a).

Climate services for adaptation

Despite their potential usefulness, literature on the actual impact (i.e. short- and long-term benefits costs across social groups and the environment) of CSs remains scarce, as most literature evaluates their effectiveness on the basis of user uptake (Boon et al., 2022; Perrels et al., 2020; Vaughan et al., 2019). This can be explained by the short-term nature of many projects, as well as the difficulty of evaluating the impact on longer time horizons (Boon et al., 2022; Perrels et al., 2020). Consequently, seasonal and sub-seasonal forecasts remain the most common typologies of CSs among users and researchers alike, as these are more established, and yield immediate outcomes (Bruno Soares & Buontempo, 2019; Christel et al., 2018; C. D. Hewitt et al., 2020). Boon et al. have criticized the short-term focus of most monitoring and evaluation processes, underscoring the need for an "*uptake-output-outcome-impact*" approach, instead (Boon et al., 2022). Despite these difficulties, information on long-term impact is believed to be indispensable for the effective use of climate services in the decision-making process of climate adaptation strategies (hereinafter referred to as adaptive decision-making) (Boon et al., 2021; Brasseur & Gallardo, 2016; C. D. Hewitt et al., 2020).

The no-regret assumption associated with CSs use and development is exemplified by the lack of mentions of maladaptation or unintended consequences in the major frameworks and projects that guided the development of CSs over the past two decades (e.g. Hewitt et al., 2012, Jacob et al., 2015; Hewitt et al., 2020, JPI-Climate ERA4CS, 2022). However, this assumption ignores the complex nature of the climate-adaptive decision-making processes. Numerous studies have emphasized the complexity of this process and the limitations of climate information as the sole trigger for adaptation measures (Kirchhoff et al., 2013; Moser, 2014; Vulturius et al., 2020). For example, Vulturius et al. (2020) showed how, in the case of forest management, information from peers is often is more influential than top-down information from experts. In the case of flood response, repeated false alarms or inaccurate warnings can lead to a decline in trust in the service, undermining its effectiveness (Sawada et al., 2022). Furthermore, in a study on the Brazilian state of Ceará, Lemos et al. (2002) showed how farmers resisted the introduction of a drought forecasting triggered seed distribution program, as it deprived them of the agency on when and what to plant (Lemos et al., 2002). In the case of the Louisiana Coastal Master Plan in 2017, a nature conservation group and the local shipping industry quarreled over the fate of a natural channel in the Mississippi delta, both groups using CSs to support their contrasting interests (Nost, 2019).

Adaptation in the Socio-Ecological system

Concurrently to the development of CSs, the field of adaptation science has begun to investigate the challenges of designing adaptation measures in complex human-nature systems (Eriksen et al., 2011; Larrosa et al., 2016; Naylor et al., 2020; Verburg et al., 2016), especially when these systems are undergoing rapid changes due to external factors, such as climate change and socio-economic shifts (Fedele et al., 2019; Lindenmayer et al., 2010). Consequently, a systemic approach that looks at the system as a whole became necessary to understand the long-term impact of adaptation measure. Many fields related to climate adaptation have long recognized the importance of a systemic perspective, as demonstrated by the wealth of these type of studies in socio-hydrology (Di Baldassarre et al., 2017; Di Baldassarre, Kooy, et al., 2013; Di Baldassarre, Viglione, et al., 2013; Garcia et al., 2020; Girons Lopez et al., 2017; Ridolfi et al., 2020; Savelli et al., 2022), conservation ecology (Larrosa et al., 2016), social-ecology (Fedele et al., 2019, 2020), and sustainable development (Moallemi et al., 2022; Tellman et al., 2018).

Socio-Ecological System (SES) theory is central in the study of adaptation and maladaptation in complex systems (Mangan et al., 2016). The concept of SES evolved from "general system theory" during the mid-20th century encompassing the complex web of interactions between social and ecological components of a human-natural system (Musters et al., 1998; Nabavi et al., 2017; Richardson, 2011). Feedback mechanisms play a pivotal role in SESs, influencing their behavior and posing challenges for adaptation (Bartelet et al., 2022; Fisher-Vanden et al., 2013; Pruyt, 2013; Sterman, 2001; Verburg et al., 2016).

Feedbacks mechanisms, or feedback loops, are chains of causal relationships that can lead to self-reinforcing or self-balancing effects in the system, and are the source of the dynamic complexity a system (Sterman, 2001, 2014). Understanding feedbacks within SESs is essential for effective decision-making and adaptation efforts, as it shifts the focus from external problems to endogenous issues, in line with contemporary conceptualizations of risk management over hazard management (Chandler, 2019; Gain et al., 2020; Naylor et al., 2020). Complex systems often resist linear solutions due to unidentified feedback loops, leading to unintended consequences (Sterman, 2001, 2014). One such example is the "*levee effect*", where the construction of levees to reduce the frequency of flooding, unintentionally enables more urban development in flood-prone areas, leading, paradoxically, to increasing flood risk (White, 1945; Di Baldassarre et al., 2013; Haer et al., 2020). Recognizing and addressing these complexities and feedbacks is critical for managing SESs sustainably and enhancing resilience.

Often, approaches to adaptation forego complex dynamics and solely rely on incremental adaptation (i.e. short-term fixes) that attempt to address the problem's symptoms (Fedele et al., 2020; Magnan et al., 2016). This can be explained by the salience bias, as short-term issues are given precedence over long-term ones (Bordalo et al., 2020; Garcia et al., 2020; Garcia & Islam, 2021). Yet, these types of approach can give rise to maladaptation if the complex feedbacks within the system are overlooked (Hallett & Hobbs, 2020; Larrosa et al., 2016; Magnan et al., 2016; Moallemi et al., 2022). Incremental adaptation measures are often favored compared to transformative ones since the latter consist systemic changes addressing an issue at the root, which can be contentious (Boon et al., 2021; Fedele et al., 2019, 2020). Still, researchers point out that transformative adaptation is in many cases necessary for adaptation to be sustainable (Boon et al., 2021; Fedele et al., 2019, 2020; Kates et al., 2012), and that CSs can be instrumental in deciding which adaptive pathway to follow (Ashley et al., 2020; Boon et al., 2021; Nost, 2019).

To deal with complex processes, many fields working with complex systems have employed theories and methodologies developed by the business management world in their investigations, such as system dynamics and system archetypes (Senge, 1990; Sterman, 2001). This is the case, for example of ecological management (Hallett & Hobbs, 2020), socio-hydrology (Di Baldassarre et al., 2017; Gain, Sarwar Hossain, et al., 2020), climate change adaptation (Fedele et al., 2020), and sustainable development (Moallemi et al., 2022). However, in the research on CSs this perspective remains novel.

Aim of the study

With the exception of a handful of studies (e.g. Nost, 2019), research on CSs does not explicitly include an analytical angle on maladaptation, instead relying on the no-regret assumption. Yet, even these few instances are composed of descriptive case studies, and do not offer a generalized perspective of the mechanisms linking CSs and adaptation/maladaptation. To fill this gap, this study aims at demonstrating how the use of CSs in climate adaptation strategies can present the risk of maladaptation, as well as laying the groundwork for maladaptation assessments in the field of CSs by identifying effective tools and theories. To this end, we examine five cases across Europe with the scope of drawing mechanisms of maladaptation that can be generalized across them. We employ system archetypes as a theoretical underpinning to describe these mechanisms, identified through a questionnaire and a series of interviews with stakeholders (SHs). The *pathways to maladaptation framework* (Magnan et al., 2016) is then used to identify whether the processes described by the archetypes constitute cases of maladaptation. The type of maladaptation that these processes describe is then identified using the *typology of maladaptation* developed by Juhola et al. (2016). This research shows the importance of assessing the risk of maladaptive outcomes when developing CSs or when designing adaptation strategies that rely on them, as well as identifying tools and theories to do so. Additionally, it provides a first conceptualization of the interactions between CSs and adaptation/maladaptation, which can support CSs developers and adaptation managers in accounting for such systemic perspective in their operations.

The case studies examined are part of the I-CISK project (icisk.eu), which is an ongoing EU project where CSs are co-developed by a team of academic and research institutions together with partners on the ground forming Living Labs (LLs). LLs offer the advantage of having a two-way interaction between SHs and researchers as CSs are co-developed with an action research approach aimed at producing change through research. The processes described in this paper, while realistic, are theoretical in nature, and do not necessarily constitute an attempt at forecasting dynamics in the LLs. Instead, it is part of the goal of I-CISK to avoid maladaptation.

Theoretical framework

System archetypes

In this paper, we use system archetypes as tools to formalize and analyze the interactions between CSs and (mal)adaptation (Meadows et al., 1972; Senge, 1990). Archetypes are simple system models characterized by feedback loops giving rise to dynamically complex emerging behaviors (Mirchi et al., 2012; Wolstenholme, 2003). Due to their simplicity, system archetypes are used for conceptualizing complex systems (Elsawah et al., 2017), and for identifying dynamics across socio-ecological and socio-technical systems (Moallemi et al., 2022). Originally introduced by Peter Senge (1990) in the *The Fifth Discipline*, system archetypes are theoretically rooted in system dynamics modeling. More recently, they have been exploited as useful tools to explore challenges arising from complex systems interactions, such as the impact of ecological intervention measures (Hallett & Hobbs, 2020) and trade-offs between different Sustainable Development Goals (SDGs) (Moallemi et al., 2022). While the exact number of archetypes and their names vary depending on the literature used, the dynamics that they represent are largely the same. This study relies on the list of archetypes presented by Moallemi et.al (2022), shown in Table 1.

Maladaptation

Maladaptation can be defined as the "*action taken ostensibly to avoid or reduce vulnerability to climate change that impacts adversely on, or increases the vulnerability of other systems, sectors or social groups*" (Barnett & O'Neill, 2010, p. 2011). Juhola et al. (2016) offer a typology based on three types of maladaptation: *Rebounding vulnerability*, where the maladaptive nature of the measure reflects on the subject that employed it, often after some lag time. *Shifting vulnerability*, where vulnerability is transferred from one subject to another in the system, sometimes giving the illusion of successful adaptation to the first actor. *Eroding the conditions for sustainable development*, where the reduction of vulnerability is accompanied by a degradation of the system that precludes sustainable development. The key difference with shifting vulnerabilities is that vulnerability is transferred to the wider system.

Adaptation measures always imply the risk of maladaptation (Eriksen et al., 2011; Magnan et al., 2016). Fig. 1 shows, as an example, the simple conceptualization of the relation between vulnerability and maladaptation proposed by Magnan et al. (2016), which depicts the relation as a feedback loop linking the two variables, where increased vulnerability drives the rising risk of taking maladaptive measures, which in turn further increases vulnerability. System archetypes fits the dimensions of maladaptation identified by Magnan et al. (2016), as they are, by definition, complex processes whose spatial and temporal dimensions are represented through their structure. Magnan et al (2016) also describe five mechanisms leading to maladaptation, which they name the *pathways to maladaptation framework*, adapted from previous work from Barnett and O'Neill (2010). While the first mechanism in the

Table 1
Eight of the most common system archetypes, as identified by Moallemi et al. (2022).

Archetype	Description	Dynamic behavior
Fixes that fail	Intervention is carried out to tackle the symptoms of a problem without considering unintended outcomes. Overtime the intervention itself worsens the state of the issue as it negatively impacts its root causes.	Despite increasing effort, progress slows down and conditions worsen.
Band-aid solutions	A short-term intervention tackles the symptoms of an issue offering immediate returns. This diminishes the need for long-term intervention. The root causes of the issue remain unaddressed.	Slowing progress despite increasing efforts. More and more focus is given to short-term solutions with consequent long-term issues.
*Eroding ambitions***	The complexity of the system creates uncertainty about outcome of certain measures. As a consequence, the goals are lowered so they can be met more easily.	Progress increases but towards progressively less ambitious goals.
*Downplayed problem**	Ignoring trade-offs in the measures take leads towards a situation where problems initially considered secondary become unsurmountable.	Initial progress followed by rapid decline once trade-off thresholds are crossed.
*Escalating tension**	Progressively increasing efforts on one issue leads to an equal response from another part of the system. Instead of fixing the issue, more and more resources are sunk in an attempt from the two parts at balancing each other.	The initial problem cannot be solved as the system continuously increases the required threshold to fix it. New issues arise as a consequence.
Success to the successful	Resources are divided according to the performance of different actors. As a consequence, actors with more initial resources progressively benefit more and more from the intervention, at the expenses of the others.	Inequality increases.
*Limits to growth**	Intervention depends on finite resources without addressing it.	Progress is slowing and stops as resources are depleted.
*Tragedy of the commons***	Actors pursue goals in their own interests, despite all relying on a limited resource pool.	The resources in the resource pool are progressively depleted and progress slows down.

* not identified during the desk research.
** theorized through the desk research but discarded in later stages of the methodology.

framework refers specifically to increasing greenhouse gasses, we argue that the same mechanism is valid when it comes to increasing the exploitation of any limited resource fundamental for the well-being of the system. This said, the five mechanisms are:

- *Increasing resource exploitation:* While increasing resource exploitation might address immediate current needs, this can create a positive feedback which can escalate long-term maladaptation risk.
- *Disproportionally burdening the most vulnerables:* Adaptation can be maladaptive if meeting the needs of one group comes at the expenses of a more vulnerable one.
- *High opportunity costs:* The cost of a certain measure should not be higher than equivalent alternatives.
- *Reduce incentive to adapt:* Actions become maladaptive when they discourage adaptation, such as by promoting unnecessary dependence, disincentivize community participation, or penalizing early adopters.

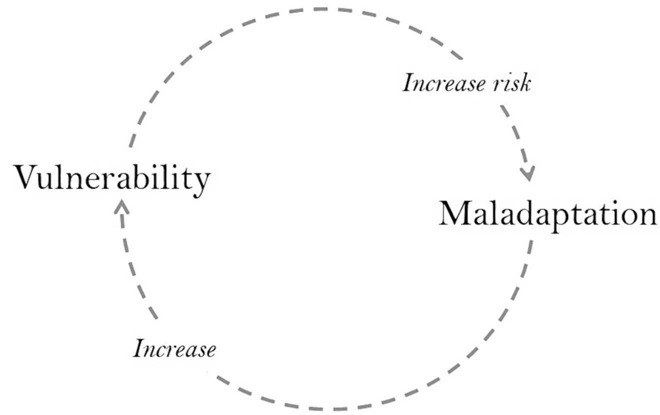

Fig. 1. Simple conceptualization of the reinforcing feedbacks between vulnerability and maladaptation
adapted from Magnan et al. (2016).

- *Path dependency*: Present choices define the future adaptation options, either by locking-in irreversible adaptive pathways, or by reinforcing the sunk investment fallacy.

Methods and data

This study follows a grounded theory approach in its methodology by relying on iterative data-collection and analysis steps, each contributing to the development of the study's hypotheses. We identified system archetypes and evaluated maladaptation in four steps. First, a desk research of the socio-ecological contexts and the challenges that each case study is trying to address by developing CSs. This step allows us to identify a set of possible processes that could be reconducted to specific archetypes. Second, a survey was devised specifically to scope for the archetypes identified. Based on the results from the survey (reported in the Supplementary materials), the processes identified in each case were described using system archetypes. Third, the results from step two are presented to expert SHs from each case study during a series of interviews. The interviews allowed us to evaluate our hypotheses (i.e. the archetypes identified) and readjust them according to the SHs' indications. Finally, the last step uses existing theories to define whether the processes identified could be described as maladaptive and what type of maladaptation was observed. This last step of the methodology does not follow grounded theory and relies instead on deductive reasoning. The following section explains in detail the methodology (Fig. 2).

During the desk research phase, the following information was collected and analyzed for all case studies: i) environmental, social, and economic characteristics (see e.g. Masih, 2022); ii) the hazards that the region is exposed to; iii) the existing CSs, their use, their users, and their limitations; iv) the current needs for CSs; v) the SHs present and those involved in the development of the CS; and iv) the expected outcome with regard of CSs co-developed through I-CISK. Based on the findings from the desk research, an initial set of archetypes was hypothesized.

Following the desk research, a survey was devised so that each question would scope for one or more archetypes; this is summarized in the supplement (table S.1 and figures S.1 to S.14). The survey was addressed to 1 to 3 "leaders" for each case study. Leaders are SHs who are both part of the I-CISK project and active on the site and have the best overview knowledge of the various cases. The questionnaire contained both multi-choice and open questions. Optional open answers allowed the respondents to elaborate, leave comments, or add options not present in the multiple-choice question. This was particularly important as many questions could have different interpretations depending on the background of the respondents. To limit misunderstandings, a short glossary of the main terminology used was

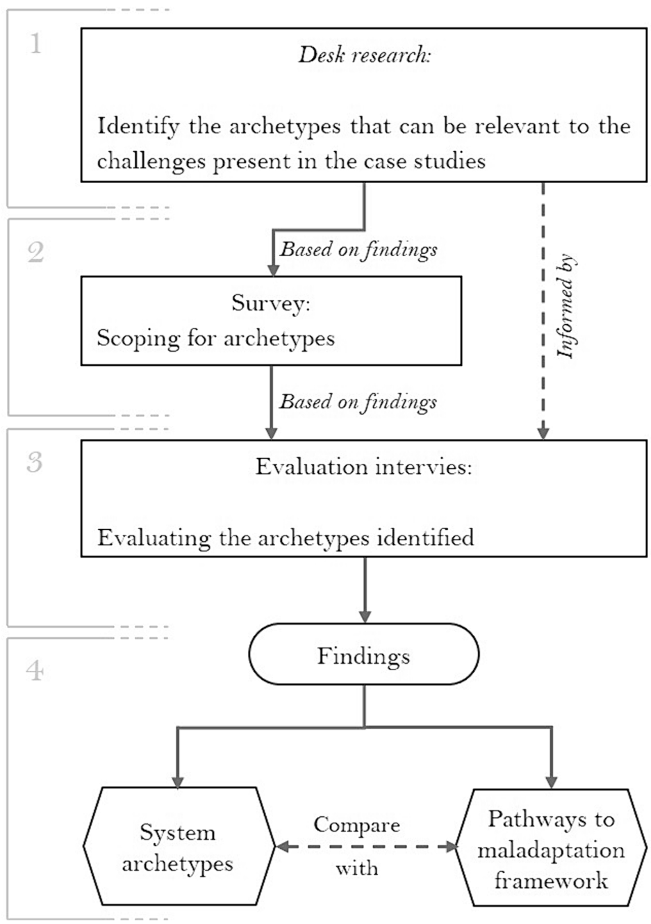

Fig. 2. Flowchart of the methodology utilized in this research.

added at the beginning of the questionnaire. The survey received 13 answers from the 5 case studies and is available in the supplement to this paper. Table S.1 in the supplement shows the questions present in the survey, and how they were used to scope for various system archetypes. Figure S.1 to S.14 in the supplement show the results from the survey. The survey was carried out over the period March to June 2023. Archetypes not identified in this step were not investigated.

The results from the survey were then used to construct system archetypes relevant to each case study. These were then discussed with the leaders in a series of interviews, carried out between May and September 2023, where the applicability of the archetypes to their respective contexts was evaluated, and the dynamics presented were adjusted to best fit the SHs' understanding of the processes ongoing in their region. The results were discussed from a theoretical perspective as, while the processes identified are realistic, they do not necessarily constitute an attempt at forecasting maladaptation in the case studies. The risk of maladaptation was openly discussed with the SHs as the CSs that I-CISK is co-developing are explicitly trying to avoid these pitfalls.

In the final step, the *pathways to maladaptation framework* (Mangan et al, 2016) was used to identify the mechanisms that define a process as maladaptive. To be deemed maladaptive, one or more of the mechanisms present in the framework needs to be identified in a case study. In this step, archetypes and processes that could not be identified as maladaptive were discarded and are not presented in this paper. After identifying which processes constituted cases of maladaptation, the type of maladaptation observed was described using the *typology of maladaptation* devised by Juhola et al. (2016).

Case studies

This study focuses on five case studies across Europe, selected among the partners of the I-CISK project where maladaptive processes could be identified through the questionnaire and interviews described in the methodology section (Fig. 3). In these case studies, CSs are being collaboratively developed with end-users from various sectors. Each case is defined by its own climate-related challenges, including droughts, floods, and water quality issues (Masih, 2022). Table 2 provides an overview of the case study and of their challenges.

Results and discussion

Identifying system archetypes

Through the desk research step, five system archetypes were identified among the case studies examined: *fixes that fail*, *band-aid solutions*, *success to the successful*, *tragedy of the common*, and *eroding ambitions*. However, the last two archetypes were discarded in later steps of the methodology. This section describes the process that led to the identification of the archetype presented in this paper, as well as the decision to discard two of them.

From the desk research, we identified a preference towards short-term CSs that address the immediate needs of the SHs, disregarding possible long-term consequences to the SES, leading us to hypothesized the *fixes that fail* archetype. Emerging was also the tension existing between long-term and short-term CSs (short-term being seasonal to interannual predictions, while long-term being decadal and end-of-century projections (Li & Ding, 2015)) (figure S.6). While the inclusion of long-term perspectives is considered necessary to ensure long-term sustainability and avoid maladaptation, most case studies showed far more interest in the short-term CSs, especially seasonal forecasting (figure S.6 and S.10). This is likely due to the urgency of responding to immediate concerns which supersedes that of focusing on issues perceived as secondary or further in time. It was conjectured that the benefits that a short-term CS could detract from pursuing long-term CSs, and the systemic benefits that they would bring, leading to a situation of competition of interests between short-term and long-term CSs. This was hypothesized using a second archetype: the *band-aid solutions* archetype.

The third archetype theorized was that of the *success to the successful*. This archetype was identified in the cases where not all the SHs who could benefit from the use of CSs were included in the co-creation process equally. This can be due to a lack of resources from representatives of those sectors to participate, or simply a lack of existing networks when setting up the SH platform. In some cases, this means that certain sectors are not represented in the co-creation process (figure S.9). In other cases, while representatives of all sectors might be present, these only represent the larger players with the knowledge and resources to engage in the co-creation of CSs. Using this archetype, it was hypothesized that the players that have access to CSs, or that might manage to have the CSs fit their interest, will over time get disproportionately advantaged and benefit at the expense of the SHs who were not as included in the co-creation process.

Eroding ambitions was the fourth archetype identified during the desk research. It was observed how during the development process of CSs, the initial goals are progressively lowered. In particular, this comes at the expenses of objectives deemed secondary, such as the inclusion and representation of SHs (figure S.3, S.4, and S.5). This can also lead to a decreased usability of the service, decreasing its potential to aid adaptation. The last archetype identified during the desk research was the *tragedy of the common*. It was hypothesized that the provision of CSs that do not include a systemic perspective might increase competition among SHs, with consequent resource exploitation (figure S.14).

Despite being initially theorized based on the findings of the desk research, both *eroding ambition* and *tragedy of the commons* were

Fig. 3. Locations of the case studies.

discarded in later steps of the methodology. The responses form the survey did not allow to conclusively identify *tragedy of the commons,* which let to it being discarded after step 2 of the methodology. On the other hand, *eroding ambitions* was initially identified in the survey, and the processes that it described were confirmed during the interview sessions. However, the processes described by this archetype in the case studies were deemed not maladaptive once analyzed through the *pathways of maladaptation framework* (Magnan et al., 2016) in step 4, as they did not reflect any of the 5 pathways described by it. The following sections explores only the three cases of maladaptation successfully identified in the case studies using our methodology. Namely: *fixes that fail, band-aid solution,* and *success to the successful.*

Fixes-that-fail

Fixes that fail is a system archetype that describes a situation where a fix effective in the short-term creates side effects in the long-term which results in the need for even more fixes (Fig. 4.a).

This was initially identified in the Spanish case study, where milk production comes to rely on drought forecasting to shore its assets and become more resilient to the increasingly frequent and intense droughts. Yet, this leads to expansion of dairy farming, which in turns leads to an exponential abstraction of groundwater due to well drilling – possibly informally, as evidenced in other areas of the same region (Manzano & Custodio, 2007) – and increasing exploitation from public sources. In the long term, this leads to more groundwater depletion, potentially reducing the system's capacity to deal with drought, and aggravating its impact (Fig. 4.b).

Similarly, in the Georgian case study, wine production in the Alazani river basin is being incentivized as main regional development strategy with consequent increased irrigation needs. This development relies on seasonal climate services (i.e. seasonal streamflow forecasting) to ensuring its drought adaptive capacity. Yet, these strategies disregard the fragility of the region, as its water resources remain precarious and its risk of desertification increases (Basialashvili et al., 2015). Hence, while seasonal streamflow forecasting is being developed as a way to increase resilience to water scarcity, the development strategies that it enables might have negative long-term effects for the SES's sustainability (Fig. 4.c).

This archetype shows how CSs can be used to allow a system to initially prosper despite it using resources unsustainably, while the delayed effects of resource depletion becomes more and more severe until the system becomes unable to continue functioning.

Band-aid solutions

Band-aid solutions archetype is characterized by a problem symptom being addressed by both a short-term and a fundamental solution: the short-term solution tackles the symptoms of the problem, producing immediate results; while the fundamental one addresses the root of the problem, which requires more time, yet brings lasting results. Consequently, the short-term solution is progressively favored because of its immediate returns at the expense of the fundamental one. This comes with long-term consequences as the root causes of the problem remain unaddressed (Fig. 5.a). The archetype is similar to *fixes that fail* as they both show the risk of unintended consequence, yet it expands on it by adding a second set of paired feedbacks highlighting the trade-off between short-term fixes and transformative solutions (Moallemi et al., 2022). It was identified across three different case studies, namely: Spain; Italy; and the Netherlands.

In the context of the Spanish case study, it has been observed that milk production has emerged as a lucrative source of livelihood. Although milk production currently offers economic advantages, it also requires significant resources, particularly in terms of water usage and groundwater pollution from manure and fertilizers. Conversely, the traditional agroecological landscape known as the "dehesa" presents a more resilient option in the long term despite its lower economic output. To shore its assets from increasing drought risk, milk production can benefit from seasonal CSs. Paradoxically, this can exacerbate the challenges in preserving the dehesa system, due to decreasing water quality and rising pressure to shift to milk production. Long-term CSs such as climate projections can instead serve as a guide for climate change adaptation strategies, creating a more resilient system in the process by promoting the preservation of the dehesa. This example shows the tensions that can arise between different types of CSs, as these favor different adaptive outcomes. Fig. 5.b illustrates the Spanish case study.

A similar case can be observed in Italy, where the sustainability of the agricultural system in the Secchia and Panaro River (and the Po valley more in general) is in question as overreliance on irrigated agriculture might be unsustainable for the hydro-ecological system in the long run. Increased water consumption comes at the expense of environmental water needs and water quality, as water scarcity increases the concentration of pollutants in the water. Short-term CSs could help make unsustainable water exploitation more resistant to transformation, generating overconfidence in handling incoming droughts. On the other hand, long-term CSs can help stir a transformation towards a more sustainable system. Hence, integrating, long and short-term perspectives in the same service could help prevent maladaptive outcomes. Fig. 5.d exemplifies these dynamics.

In the case Dutch case study, farmers rely on short-term technical measures (both private and from the water authority) to reduce salt intrusion. These measures are informed by seasonal streamflow forecasting. Farmers benefit from these types of measures because they allow them to shore their crops without having to consider more transformative measures, such as shifting crops. Additionally, farmers might be slow in adopting transformative adaptation as investment in a specific crop comes with additional investments in agricultural infrastructures that might not work for different crops (e.g. silos). Consequently, reliance on short-term solutions might make the farmers more resistant to embracing transformative solutions, as they are seen as less profitable (Fig. 5.c).

CSs have the potential to both preserve unsustainable systems and

Table 2
List and description of the case studies examined.

Case study	Description
Georgia: Alazani river basin	The Georgian case study is located in the Alazani River basin and faces a range of climate-related hazards like floods, landslides, and droughts. The region is also affected by desertification in its Easters reaches (Basialashvili et al., 2015). Sectors like agriculture, hydropower, and tourism are vulnerable. The National Environmental Agency (NEA) provides meteorological and hydrological information, weather forecasts, and bulletins despite significant gaps in sub-seasonal forecasts, tailored products, and hydrological datasets. In this case, the SHs seek to enhance CSs in the region improving observation, research, modeling, and user engagement. Seasonal and sub-seasonal streamflow forecasting systems are the main focus of the LL.
Greece: Island of Crete	The Greek case is located on the island of Crete, which is experiencing high climate variability and projected climate change impacts. The primary sector of interest is tourism, while other secondary sectors are also represented; namely: water management, transportation, and energy. Notably, agriculture, the main occupation on the island, is not represented among the SHs. The CSs under development aim to address sectoral needs at various scales, focusing on seasonal and sub-seasonal forecasting of climate indices impacting tourism.
Italy: Secchia and Panaro river basins	The Italian case study is situated in the Emilia Romagna region, specifically Modena and Reggio Emilia provinces. It focuses on surface water resource availability, management, and exploitation. It engages a diverse set of SHs including industrial, agricultural, monitoring, and policy-making interests. The Italian case focuses on developing CSs that can be used by water managers for water allocation purposes.
The Netherlands: Rijnland region	The Dutch case is situated in the Rijnland region, between the cities of Amsterdam and Den Haag. The area faces issues of insufficient fresh water during low-flow periods of the River Rhine, impacting agriculture, nature conservation, and recreational use of the water. The water board of Rijnland must make decisions during such events, including activating additional inlets and limiting ship-lock operations. Here, the project focuses on balancing the interests of agriculture, water tourism, and water management through co-developing sub-seasonal forecasts that can allow the waterboard to make decisions which respect the interests of all SHs' groups.
Spain: High Guadalquivir and Guadiana catchments	The Spanish case is situated in the Guadalquivir and Guadiana catchments in northern Andalusia, focusing on the Los Pedroches region and on the Sierra de Cazorla, Segura, and Las Villas Natural Park. The region is characterized by a sub-humid Mediterranean climate and experiences variable rainfall patterns and temperature fluctuations that impact agriculture, livestock farming, and agro-industry. Many of the users access water by drilling wells, sometime informally. Illegal well drilling is well documented in other areas of the same regions (Manzano & Custodio, 2007). In this LL, the I-CISK project aims to develop CSs to address drought risk by providing seasonal forecasts, and long-term hydrological projections.

facilitate their transformation. For instance, when short-term focused, they may enhance the resilience of unsustainable practices, leading to increased damage over time. Conversely, CSs can also provide the essential long-term perspective needed to initiate and guide systemic transformations. This example shows how different CSs can inform different adaptive pathways (Fig. 5.a).

Success to the successful

The *success to the successful* archetype describes a scenario where multiple actors compete for limited resources, the most successful competitors securing a disproportionately larger share of these resources, gradually accruing more advantages at the expenses of other actors (Fig. 6.a). These dynamics were theorized in two case studies: the Netherlands, and Greece.

In the Netherland case study, SHs involved in CSs development primarily represented the agricultural sector. In contrast, private recreationists and the tourism sector were less vocal. This discrepancy mainly stemmed from the maturity of farmer groups in collaborating with authorities and scientific institutions, while tourism and recreationist groups tended to remain unorganized. This situation lead to a co-creation process dominated by farmer groups, which, in turn, may steer CSs development toward their interests. However, if efforts are made to include recreationists in discussions and CSs co-creation, it is possible to prevent these dynamics (Fig. 6.b).

The Greek case study presents two instances of these dynamics at play. Firstly, the development of CSs in Crete primarily benefits the tourism industry, despite agriculture being the predominant livelihood on the island (Fig. 6.c). Surprisingly, agriculture groups are not represented among the SHs influencing the co-creation of these CSs. Instead, the only private SH group consisted of tourism industry representatives, particularly hotel owners. This is the result of the tourism industry displaying greater maturity in using and developing CSs, motivating its participation in the co-creation process. CSs are expected to benefit tourism by allowing it to prepare for climate variability and change. However, a growing tourism sector comports increased costs of living on the island, making agriculture a progressively less viable livelihood option, all the while the tourism industry might benefit from higher living costs. This situation can harm the sustainability of rural agriculture already affected by drought and climate change, further exacerbating the income gap between the two sectors. Instead, co-creative projects aiming to offer CSs in function of the challenges faced in a certain region, and not depending on a contract with one sector alone, should strive to achieve representation of relevant SHs. Alternatively, agriculture's interest can be indirectly addressed through the involvement of water managers on the island in the co-creation process. Water managers make the ultimate decisions regarding the allocation of water resources, and priority is given to agriculture over tourism in case of scarcity. Thus, CSs that consider the interests of both tourism and agriculture can be instrumental in prevent escalating income inequality on the island.

The second case from Greece demonstrates how a similar dynamic can also occur within the same sector when smaller and larger tourism businesses participate in the co-creation process (Fig. 6.d). In this case, larger companies can carry more weight in the co-creation platform, primarily due to their greater resources and maturity in working with scientific institutions and with CSs. Nevertheless, developing public CSs can play a crucial role in providing smaller companies with access to climate information by developing open-source tools and increasing awareness. Being aware of these processes can help counteracting the development of a *success-to-success* dynamic, empowering smaller companies to engage in climate-informed decision-making.

The impact of CSs on inequality can vary depending on accessibility and the representation of interests. Groups with more access to resources and knowledge can reap the benefits offered by CSs more than their competitors and in co-creation processes, groups that are more vocal can stir the creation of CSs toward their interests. The archetype illustrates how one group can benefit more than others from CSs and their development, and suggest that the inclusion of the interests of different actors and sectors in the co-creation process can prevent the development of *success-to-success* dynamics in the first place.

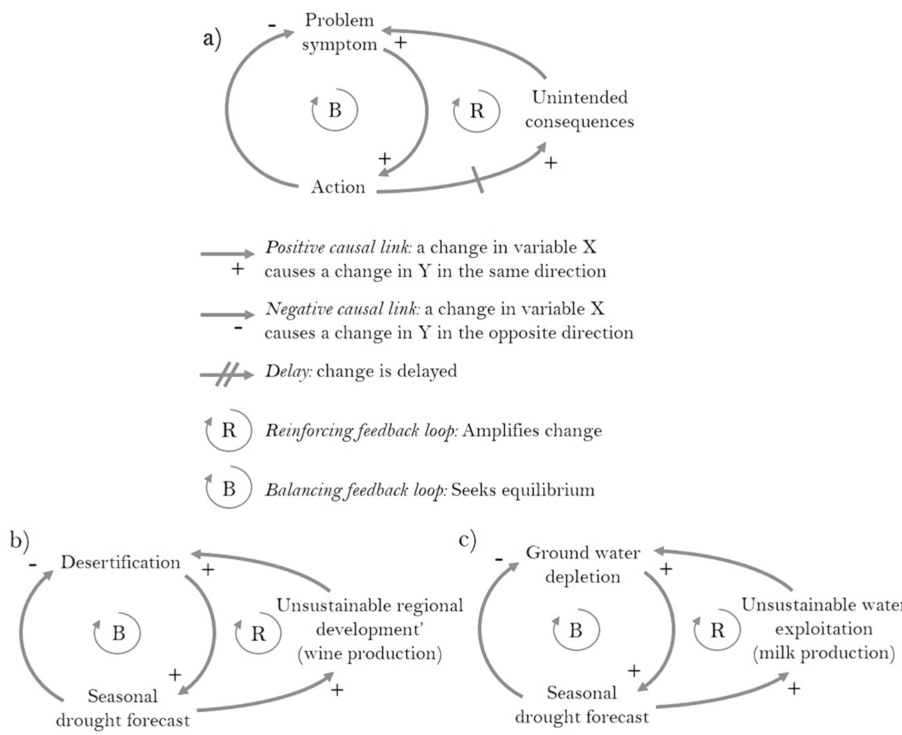

Fig. 4. Fixes-that-fail solutions as a generic dynamic (a), and as identified in the Georgian (b) and in Spanish (c) case studies.

Identifying maladaptation

The processes identified in the five case studies were then compared to the mechanisms of maladaptation described by Magnan et al. (2016) in the *pathways to maladaptation framework*. In the cases of *fixes that fail* and *band-aid solutions* in Spain, Italy, and Georgia, short-term CSs could lead to increased resource exploitation, as their use is instrumental in making unsustainable practice more resistant to drought risk. In these three cases, and in the case of the *band-aid solutions* case in the Netherlands, these unsustainable practices can become dependent on short-term CSs (*path dependency*). This can come at the expenses of the use of long-term CSs which could instead be instrumental in driving transformative adaptation, *reducing the incentives to adapt*. Finally, in the case of Greece and in the case of the interaction between the agricultural and recreational users in the Netherlands, CSs can give advantages to some actors at the expenses of more vulnerable ones (*disproportionally burdening the most vulnerable*).

Using the *typology of maladaptation* developed by Juhola et al. (2016) to classify the type of maladaptation observed, it becomes clear how the three cases of *success to the successful* archetype, can be classified as *shifts in vulnerability* from the successful actor to the less successful ones. For example, while the tourism sector might see its vulnerability to increasing frequency of climate extremes decreasing thanks to the use of seasonal forecasting, its success comes at the expense of an already fragile agricultural sector which employs a large share of the population on the island of Crete. The two cases of *fixes that fail* can be identified as examples of *rebounding vulnerability*. The expansion of intensive wine and milk productions in already fragile environments can damage the actors in the long-term. Finally, the band-aid solutions case can be attributed to examples of a combination of the *erosion of the conditions for sustainable development* and *rebounding vulnerability*. One the one hand, overreliance on short-term measures prevents or delays transformative measures to be taken, hence hindering sustainable development. While at the same time, the system itself pays the long-term consequences of these measures short-sightedness.

The findings from this section are summarized in Table 3.

Conceptualizing maladaptive processes

In this study, we showed the potential of system archetypes as tools for ex-ante assessment of maladaptive scenarios arising from the use of CSs. First, the *fixes that fail* archetype illustrates how CSs can inadvertently enable a system to thrive despite unsustainable resource use, leading to a compounding effect of resource depletion until the system becomes unsustainable (Fig. 7.a). Second, the *band-aid solutions* archetype reveals that CSs can either perpetuate unsustainable systems or catalyze their transformation. Short-term-focused CSs may bolster the resilience of unsustainable practices, exacerbating long-term harm, while long-term-focused CSs can guide systemic transformations effectively. Nonetheless, the immediate advantages brought about by short-term CSs disproportionately favor reliance on these rather than on the long-term ones (Fig. 7.b). Lastly, the *success to the successful* archetype delves into how CSs can exacerbate existing inequalities. Groups with superior access to resources and knowledge can disproportionately benefit from CSs, particularly when more assertive in co-creation processes (Fig. 7.c). To mitigate potential inequality, it is essential to engage in co-creation processes that ensure the representation of all SHs' interests (Lemos et al., 2012; Perrels et al., 2020; Vincent et al., 2018, 2020). This approach not only reduces the risk of creating disparities in CS access but also underscores the importance of including diverse actors and sectors to forestall the development of *success to the successful* dynamics.

Our results demonstrate how ex-ante assessment of the risk for maladaptation should be considered when designing or employing CSs. While the inclusion of climate information in adaptive decision making can improve it, the type of information, whose interests it caters, and who can access it, play a crucial role in the long-term impact of the adaptation measures. We conceptualize our findings by expanding on the framework presented by Magnan et al. (2016) by arguing that CSs respond to the needs to address vulnerability, and are made to support adaptation by providing aid for the decision-making (Fig. 8). The impact that these measures have on vulnerability will then guide future need for CSs. This views CSs as both providers and receivers of information to and from adaptation, theorized by Bruno Soares & Buontempo (2019). Yet,

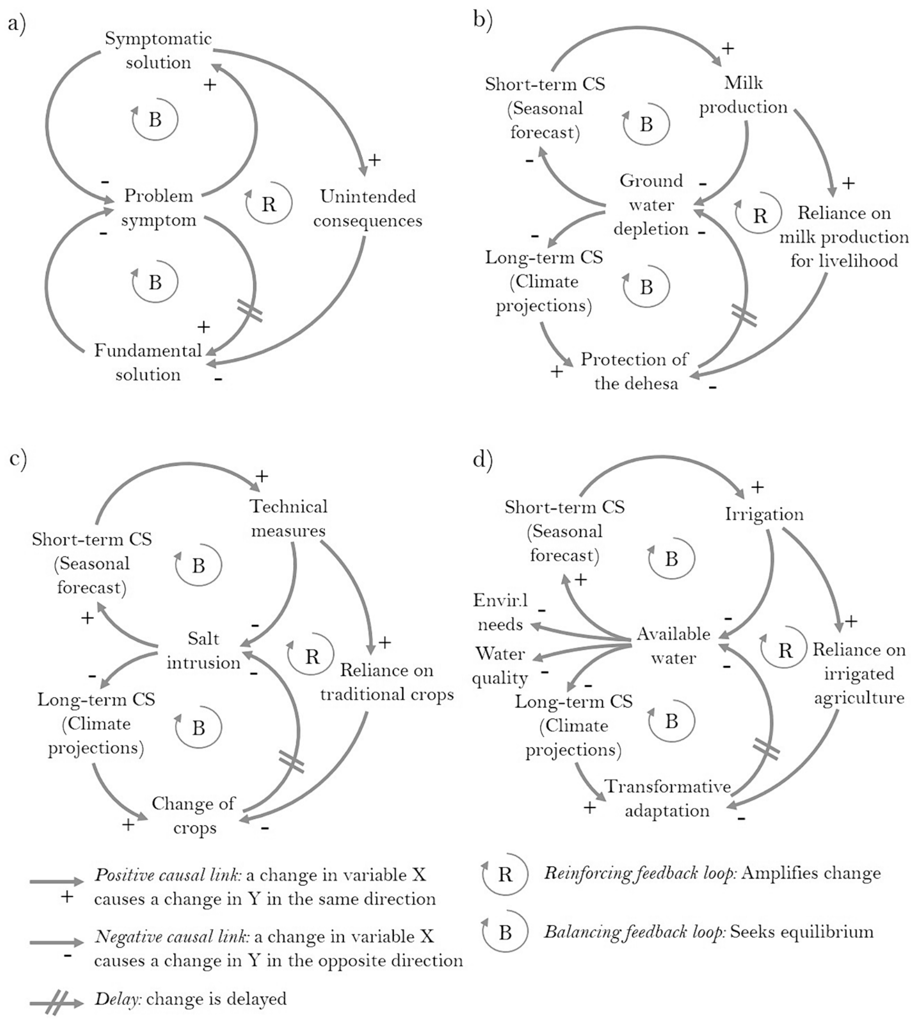

Fig. 5. Band-aid solutions as a generic dynamic (a) and as identified in the various cases: Spain (b), the Netherlands (c), and Italy (d).

as stated by Magnan et al. (2016) adaptation and maladaptation are two sides of the same coin, hence adaptation measures should always consider possible maladaptation risk. Our conceptualization adds a balancing feedback loop linking CSs, vulnerability and adaptation/maladaptation which acts parallel to the reinforcing loop theorized by Mangan et al. (2016). These dynamics were identified across all the archetypes identified. For example, in the *fixes that fail* case of Spain, the short-term focus of the seasonal forecast addresses the vulnerability of the milk production in the short term. Yet, the long-term impact on the ecosystem nullifies these effects creating more and more dependence on seasonal forecasting to address the increased vulnerability to drought caused by the increased water extraction.

Conclusions

This study demonstrates how CSs do not always guarantee "no-regret" solutions in the context of climate adaptation, as their development and application can result in unintended consequences, some of which might constitute examples of maladaptation. In our research, eight potential examples of maladaptive processes were identified across five different case studies. These were described using three system archetypes (Fig. 7). The framework provided by Mangan et al. (2016) allows us to define whether the observed dynamics constitute a significant risk of maladaptation, while the type of maladaptation observed was characterized using the *typology of maladaptation* defined by Juhola et al. (2016).

Our research definitively underscores the need for a maladaptation perspective when utilizing CSs in adaptation and offers theories, tools and frameworks to be used in this regard. System archetypes, such as *fixes that fail*, *band-aid solutions*, and *success to the successful*, provide invaluable insights into the mechanisms leading CSs to enable unsustainable practices, hinder transformative adaptation, and exacerbate inequalities. This highlights the interconnectedness of adaptation and maladaptation, emphasizing the importance of considering possible maladaptation risks when designing and employing CSs. It suggests a shift from the "no-regret" solution assumption to a more complex perspective that acknowledges the trade-offs and potential unintended outcomes of CSs. The study also stresses the significance of inclusive co-creation processes that encompass the interests of all SHs, reducing the risk of creating disparities in CS access and mitigating the development of success-to-success dynamics in CS implementation.

We argue that adaptation managers and CSs developers should include systemic perspectives that account for maladaptation and unintended consequences in their operations. By clearly connecting CSs with adaptation/maladaptation through the use of system archetypes this study lays the groundwork for the creation of tools that can be used for assessing the risk of maladaptation when developing CSs and when designing adaptation strategies using them. To this end, we provided a first conceptualization of the interaction between CSs and adaptation/maladaptation (Fig. 8), we showed that system archetypes are a suitable tool for this type of conceptualization, and we identified a framework that can be used in the evaluation of maladaptive processes, i.e. *the*

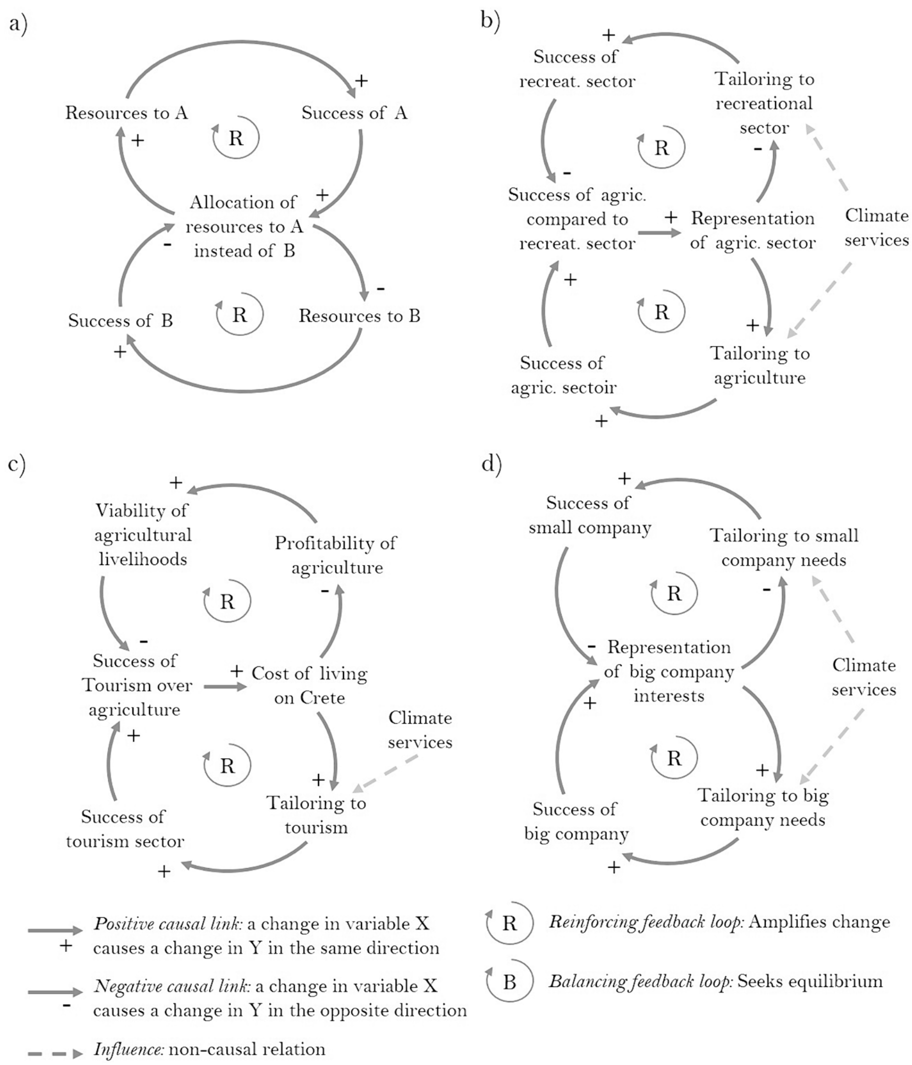

Fig. 6. Success to the successful, adapted as a generic dynamic (a) and as identified in the various cases: Netherlands (b), Greece #1 (c), and Greece #2 (d).

Table 3
Mechanisms and typologies of maladaptation identified in the various case studies. The five mechanisms are those described in the pathways to maladaptation framework by Magnan et al. (2016), while the typology is that provided by Juhola et al (2016). The acronyms in the first row meaning: Increased Resource Exploitation (ERE); Disproportionally burdening the most vulnerables (DBV); High opportunity costs (HOC); Reduced incentive to adapt (RIA); and Path Dependency (PD).

Country	Archetype	Pathways to maladaptation					Typology of maladaptation
		ERE	DBV	HOC	RIA	PD	
Georgia	Fixes that fail	☑	☐	☐	☑	☑	Rebounding vulnerability
Greece	Success to the successful #1	☐	☑	☐	☐	☐	Shifting vulnerability
	Success to the successful #2	☐	☑	☐	☐	☐	Shifting vulnerability
Italy	Band-aid solutions	☑	☐	☐	☑	☑	Rebounding vulnerability; Eroding sustainable development
Netherlands	Band-aid solutions	☐	☑	☐	☑	☑	Rebounding vulnerability; Eroding sustainable development
	Success to the successful	☐	☑	☐	☐	☐	Shifting vulnerability
Spain	Fixes that fail	☑	☐	☐	☑	☐	Rebounding vulnerability
	Band-aid solutions	☑	☐	☐	☑	☑	Rebounding vulnerability; Eroding sustainable development

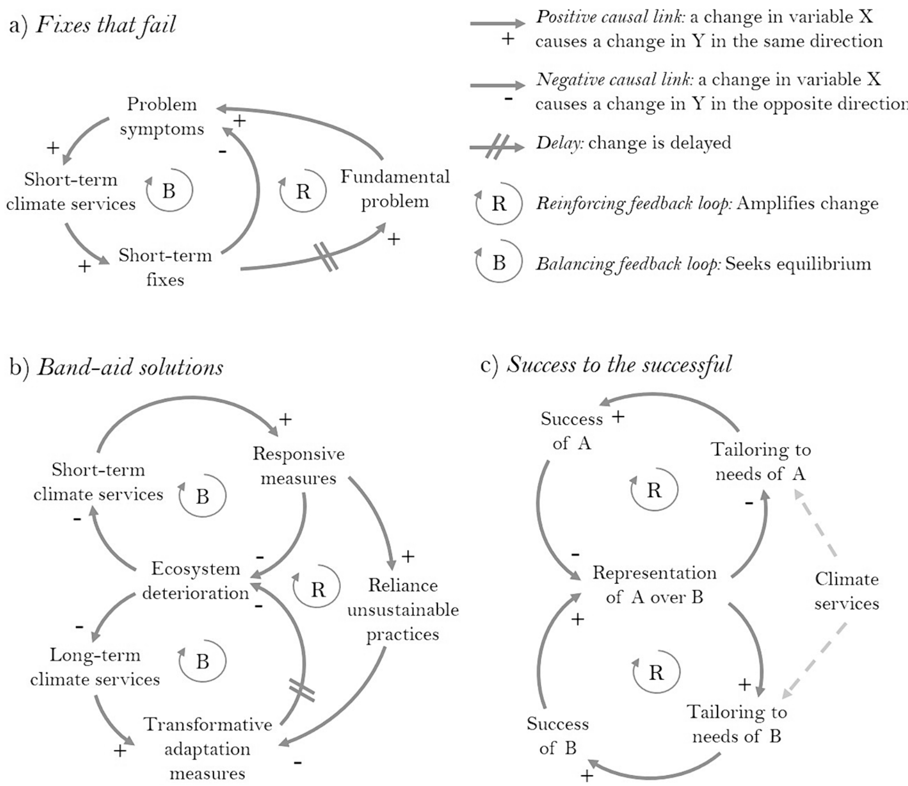

Fig. 7. Generalized archetypes of the interaction between climate services and adaptation.

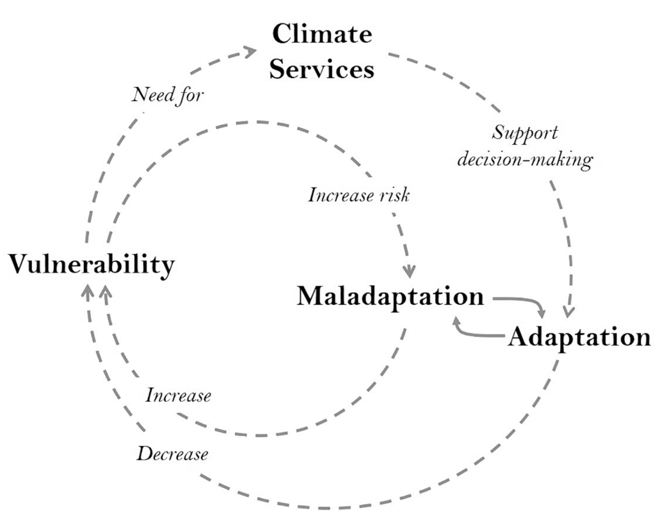

Fig. 8. Conceptualization of the interaction between CSs and adaptation/maladaptation. CSs support adaptation by providing climate information, while being designed and implemented in response to the needs of addressing vulnerability in the system. Adaptation and maladaptation are viewed as two sides of the same coin. This framework expands on the one provided by Mangan et al. (2016, page), by introducing the relation between CSs and adaptation/maladaptation.

pathways to maladaptation developed by Magnan et al. (2016). We invite for further research to be done in this area, firstly by expanding on our work to include more archetypes, second by using our framework to develop tools for the assessment of the risk of maladaptation that can be used by CS developers and adaptation managers (e.g. checklist for self-assessment, decision trees, best-practices…).

In closing, while CSs can be powerful tools for enhancing climate adaptation, their design and implementation, as well as the specific interests they serve are critical factors in determining whether they lead to adaptive or maladaptive outcomes. Given the current proliferation of CSs, it is timely for the climate adaptation community to explore more closely and consider more explicitly the long-term impacts of CSs and their potential for maladaptation.

CRediT authorship contribution statement

Riccardo Biella: Writing – review & editing, Writing – original draft, Visualization, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Maurizio Mazzoleni:** Visualization, Supervision, Methodology. **Luigia Brandimarte:** Writing – review & editing, Supervision, Conceptualization. **Giuliano Di Baldassarre:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

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Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cliser.2024.100490.

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