Mitig Adapt Strateg Glob Change (2025) 30:27
https://doi.org/10.1007/s11027-025-10217-w

How to avoid the risk of maladaptation? From a conceptual understanding to a systematic approach for analyzing potential adverse effects in adaptation actions

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Received: 11 July 2024 / Accepted: 29 March 2025

Abstract
Climate change is already affecting and altering natural and human systems, and its effects are expected to intensify over the coming decades. Adaptation is therefore imperative for future development. However, like any other anthropogenic intervention, adaptation measures can have unintended detrimental impacts and adverse effects on human and natural systems, known as maladaptation. With growing evidence of maladaptation, practitioners in the fields of resilience and climate change adaptation increasingly focus on avoiding maladaptation risks in their projects. Yet, there is still no clear understanding of how to comprehensively and systematically analyze adverse effects in adaptation actions. To address this gap, this article advances the conceptual understanding of maladaptation and elaborates a pragmatic approach for examining, identifying, and diagnosing maladaptation risks in adaptation measures. Starting by breaking down the concept of maladaptation into analytical components (i.e., drivers, mechanisms, dimensions, attributes, forms, and outputs of maladaptation) based on the relevant literature, we propose a new harmonized and actionable definition. Based on this new understanding, we propose a practical and systematic approach to analyze maladaptation risks at the early stages of adaptation planning. Through the proposed definition, conceptual disaggregation, and practical framework, this paper contributes to a better understanding of maladaptation and provides practitioners with means to improve the design of future adaptation measures.

Keywords Maladaptation · Adaptation planning · Risk analysis · Framework · Climate change adaptation

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Published online: 15 April 2025

1 Introduction

There is no doubt that the extensive changes in the atmosphere, biosphere, lithosphere, and hydrosphere caused by human activities have warmed the global climate (IPCC 2021). It is projected that in the upcoming years, a changing climate will increase the occurrence, intensity, spatial extent, duration, and timing of existing climate-related risks (including extreme weather events) as well as introduce new ones into natural and human systems (IPCC 2012, 2014, 2021). Human health, livelihoods, food security, water supply and economic growth will be increasingly threatened by climate-related risks (IPCC 2018). Consequently, climate change adaptation (CCA) is becoming part of new development strategies to reduce climate change's impacts and sustain the functioning of human societies and natural systems (Noble et al. 2014).

Real-world experience demonstrates that climate-related risks can arise not only from the interplay of various climatic and non-climatic factors, but also from responses to climate change that can interact unpredictably, sometimes leading to amplified or cascading effects (Simpson et al. 2021). There is evidence that poor adaptation planning has led to negative outcomes by shifting climate risks and vulnerabilities to other territories, sectors, communities, or ecosystems (Magnan 2014; Rizvi and van Riel 2015; Magnan et al. 2016; Reckien et al. 2023). Additionally, in some cases, adaptation actions have favoured certain groups or sectors by excluding or affecting others (Noble et al. 2014; Work et al. 2019). Given that justice and equity aspects are often overlooked (Pelling and Garschagen 2019; Owen 2021; Juhola et al. 2022), there have been examples where competing interests, differing values and uneven power relationships led to misallocation of resources and redistribution of social and environmental costs (Granberg and Glover 2014; Bertana et al. 2022). Thus, when CCA complexity is oversimplified, adaptation measures can have unintended consequences that could threaten the sustainable development of communities (Work et al. 2019). In CCA literature, this is described as maladaptation.

According to Ranasinghe et al. (2021), maladaptive interventions refer to a deficient adaptation measure that has unintended negative consequences that ultimately increase the risk of adverse effects of climate change on a community or ecosystem. Yet, in the literature, these interventions can also have broader implications for socio-ecological systems, as discussed in later sections of this article. For example, maladaptive actions are those that can accelerate the degradation of natural resources and ecosystems, reinforce positive feedback loops (e.g., greenhouse gas (GHG) emissions and climate change), create a pathway dependency, block development options, or relegate problem-solving to future generations (Barnett and O'Neill 2010; Granberg and Glover 2014; Magnan et al. 2016; UNEP 2019). Even if a specific action increases the climate resilience of a targeted community, sector, territory, or ecosystem in the short term, but impairs the adaptive capacity or development opportunities of other communities, sectors, territories, or ecosystems in the long term, it may be considered maladaptive (Magnan et al. 2016). Thus, maladaptation emerges as an additional concern among adaptation planners (Noble et al. 2014) and other practitioners.

In the CCA field, practitioners (i.e., adaptation planners, policymakers, scientists, researchers, consultants, technical experts, and project developers and implementers) face different challenges related to maladaptation. The first challenge concerns the conceptual understanding of maladaptation, which is crucial for informing adaptation decisions and directing investments towards sustainable measures but is not effectively operationalized in decision-making processes (Rizvi et al. 2014; Bertana et al. 2022). Currently, the maladaptation concept is analytically and operationally difficult to apply in adaptation planning

(Juhola et al. 2016; Atteridge and Remling 2017). Its poor understanding characterized by the absence of a universally accepted definition (Bertana et al. 2022) as well as a continuously evolving and contrasting conceptualization, poses several practical issues, such as its non-measurability (Granberg and Glover 2014) and a high degree of subjectivity (Noble et al. 2014). This shortfall hampers the ability of decision-makers to comprehensively evaluate adaptation options and develop effective strategies, limiting their capacity to grasp the nuanced dynamics of adaptation efforts.

The second challenge relates to the failure to account for the adverse effects of adaptation actions on both targeted and non-targeted entities (i.e., ecosystem, economic sector, community, territory, social group, infrastructure or species) and their potential to induce maladaptive outcomes across socio-ecological systems (Reckien et al. 2023). Defining clearly what comprises adaptation and how to evaluate its effectiveness is complicated (Noble et al. 2014; Reckien et al. 2023), a difficulty that extends to the identification of what constitutes maladaptation. Adaptation is a multi-dimensional, dynamic, highly interdependent and complex concept that cannot be attributed to a single decision (Granberg and Glover 2014). Assessing the outcomes of an adaptation measure is context-specific and includes understanding the relationships and interdependencies between adaptation actions and the system, as well as unforeseen events (Noble et al. 2014; Granberg and Glover 2014). Moreover, it depends on judgments conditioned by multiple factors such as the time horizon of the evaluation, baseline comparison with a selected future climate scenario, individual perspectives of harms and benefits, estimation of opportunity costs and avoided costs, the temporality effect on counterfactual thinking, and changes in local dynamics and social norms over time (Adger et al. 2005; Noble et al. 2014; Granberg and Glover 2014; Juhola et al. 2016; Atteridge and Remling 2017; Reckien et al. 2023).

The third challenge is the absence of a comprehensive framework for identifying, analyzing and timely addressing maladaptation. Little attention has been given to supporting practitioners in identifying the root causes of maladaptation during the planning and initial decision stages (Jones et al. 2015). The existing CCA literature focuses mainly on assessing adaptation measures' success in terms of equity, efficiency, and legitimacy (Juhola et al. 2022), but practitioners also urgently need to understand maladaptive effects of their interventions to fully realize the social, environmental and economic benefits of CCA (Bertana et al. 2022; Reckien et al. 2023). Apart from Boehm et al. (2020), who adapted the generic framework by Jones et al. (2015) to investigate maladaptation risks of ecosystem-based adaptation measures in the Peruvian Andes, and Reckien et al. (2023), who propose a six-criteria framework to assess the outcomes of adaptation rather than inspecting maladaptive intervention designs, there is no specific methodology for avoiding maladaptive responses in the design and implementation stages. Reid et al. (2017) propose a questionnaire for screening maladaptive outputs, however, as an *ex-post* effectiveness assessment of already implemented measures. More recently, a self-assessment checklist has been proposed to identify a short list of factors that may lead to maladaptation (REGILIENCE 2023), without providing a comprehensive and clear indication of *what* or *how* maladaptation risks may emerge. Although these efforts allow learning from other projects, they do not allow analyze maladaptation risks in depth, nor to prevent them proactively. Such an absence of practical frameworks for avoiding maladaptation obstructs the appropriate development and implementation of effective adaptation measures (Magnan 2014).

Given the lack of methods to identify, analyze and monitor maladaptation risks, Magnan (2014), Juhola et al. (2016), and Bertana et al. (2022) suggest an *ex-ante* analysis of maladaptation, which could play a crucial role in avoiding negative outcomes prior to the implementation of adaptation actions. In this regard, Magnan et al. (2016) identified three main reasons why maladaptation should be considered in early planning stages: I) to use resources, time, and efforts efficiently; II) to assist decision-makers and cooperation agencies in supporting the best initiatives; and III) to help practitioners, communities and policy-makers to design better and more robust adaptation measures. This emphasizes the necessity for a cohesive and actionable framework to analyze and address maladaptation (Atteridge and Remling 2017; Bertana et al. 2022) as well as a more refined approach to managing the adaptation cycle— from scoping to monitoring and evaluation.

Against this background, critical questions arise: *How can the concept of maladaptation be effectively operationalized to support practitioners in decision-making*? *What are key components for understanding and addressing maladaptation comprehensively*? *How can the adverse effects of adaptation actions be systematically identified and avoided in early planning stages*? To answer these questions and overcome the challenges described above, we reviewed recent progress and developments in the scientific and grey literature on maladaptation. With this study, we aim to connect the theoretical concepts of maladaptation with practical insights into their application by providing:

- A comprehensive understanding of maladaptation by breaking it down into manageable components.
- A redefinition of the maladaptation concept that helps to operationalize it.
- A systematic and proactive approach to analyze the risk of maladaptation in adaptation measures in the early stages of adaptation planning.

By doing so, we present a practical framework that comprehensively analyzes the detrimental impacts of adaptation measures and their potential to exacerbate, transfer, or induce risks, supporting practitioners in better selecting, designing, and implementing adaptation actions.

Section 2 presents the methodology adopted for the study, while Section 3 delves into the theoretical background and the state of the art of the maladaptation concept. The findings of this study encompass a dissection of maladaptation into workable components that facilitate an exploration of the associated risks (Section 4), a harmonized and more practical definition of maladaptation (Section 5), and a practical framework for an ex-ante analysis of maladaptation (Section 6). Section 7 discusses the results, their relevance, applicability, limitations, and prospects for future research. Finally, we draw conclusions from our investigation in Section 8.

2 Methodology

We conducted a systematic review of both peer-reviewed and grey literature to gain an in-depth understanding of the maladaptation concept, its practical application, and the prevailing challenges associated with it. As a first step, we looked for peer-reviewed articles in English up to February 2024 that contain the search terms “maladaptation”, “climate”, and “risk” in their titles, abstracts, and keywords (Fig. 1). This initial search yielded 156 records. Second, we limited our search by focusing on relevant subject areas related to the review, including Environmental Science, Social Science, Earth and Planetary Science, Engineering, Decision sciences, Economics, and Multidisciplinary. This criteria refinement resulted in 131 publications. Third, we meticulously screened titles and abstracts looking for explicit references to maladaptation or implicit

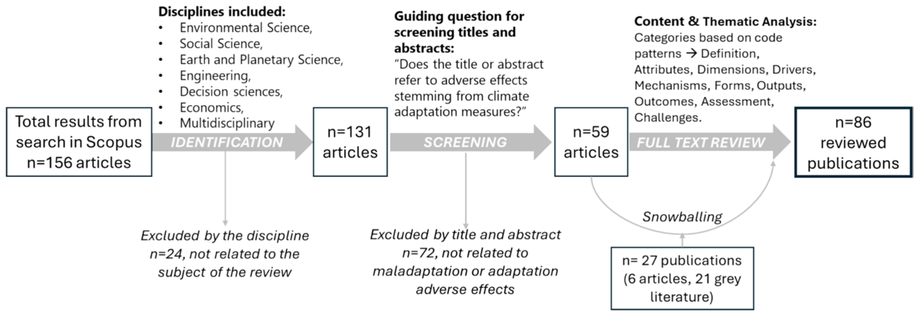

Fig. 1 Literature selection for review

examination of negative effects stemming from adaptation measures. We excluded, papers that did not focus on investigating, explaining, evaluating, or discussing maladaptation or adverse consequences of adaptation. We then selected 59 papers for full-text review. During the full-text review, we identified and included other 27 additional publications (peer-reviewed articles (n = 6) and grey literature (n = 21)) via snowball sampling, culminating in 86 reviewed documents.

The selected publications were subjected to content analysis (Berg 2006; Bernard 2012), utilizing predetermined codes that corresponded to the specific research questions (*see* Supplementary Material Table S1). For this analysis, we employed CITAVI software to organize and categorize the data. Further, we carried out a thematic analysis (Nowell et al. 2017; Thompson 2022). This involved transferring the identified codes into a thematic matrix in Excel, where we assigned each code to a thematic category. We then collectively analyzed these categories to discern patterns and responses to the research questions. The thematic categories included: *Definitions, Outcomes, Attributes, Forms, Mechanisms, Drivers, Outputs,* and *Dimensions*.

We used the same thematic categories mentioned above to unpack and break down the concept of maladaptation into actionable, simpler, and more understandable components. For elucidating a redefinition of maladaptation, we used inductive reasoning (DeCarlo 2018), considering adaptation as the antithesis or opposite end of an adaptation effort (Reckien et al. 2023). Leveraging both redefinition and conceptual disaggregation, we proposed an ex-ante approach to pragmatically identify, diagnose, and mitigate the risks of maladaptation.

3 Theoretical background

For analyzing the risk of maladaptation in adaptation planning, the first necessary step is to establish a basic understanding of risk in the context of climate change, as well as the concept of adaptation and its implications. As the concept of maladaptation is relatively new, it is also crucial to examine its evolution, how different authors have defined it, and the practical issues related to its current understanding. This section addresses these aspects in detail.

3.1 Risk and climate change adaptation

In the context of climate change, risk is *"the result of dynamic interactions between three factors: hazard, vulnerability, and exposure*" (Reisinger et al. 2020, p. 4). It can be defined as "*the potential for adverse consequences for human or ecological systems that can arise from potential impacts of climate change as well as human responses to climate change*" (ibid). Apart from the impacts of climate-related hazards, risks can also arise from trade-offs and adverse effects of responses to climate change or from unexpected outcomes of climate actions (policy, investments, technology adoption) and systems transitions (Reisinger et al. 2020; Ranasinghe et al. 2021).

Understanding adaptation is a prerequisite for comprehending the concept of maladaptation. Adaptation can be referred to as the act of being apt, the state of merging or fitting into a specific context, or the quality of adopting and integrating external elements (Simonet 2010). In a broader sense, adaptation is the process defined by steady states in which any type of system is able not only to sustain its function, structure, and identity in facing disturbances, stressors and abrupt environmental changes but also to improve its capacity to respond to new events while benefiting from the changing conditions (Nelson et al. 2007; Simonet 2010). This means that systems adapt to a wide range of changes and dynamics.

In the climate change context, adaptation is defined as "*the process of adjustment to actual or expected climate and its effects, to moderate harm or exploit beneficial opportunities*" (Ranasinghe et al. 2021, AVII- 2). CCA refers to the capacity of social-ecological systems to avoid, anticipate, manage and react in the short and long term in an adequate, effective, and timely manner to the observed, expected, and possibly some of the unforeseen impacts of climate change, climate variability, and extreme events while building resilience, meeting development's needs, and attaining human well-being (IPCC 2001, 2014; Russel et al. 2018; UNEP 2021). It is important to note that any adaptation process has as premises: (i) improve what is currently inadequate, (ii) address current risk drivers to reduce future risks, and (iii) avoid causing harm (Magnan 2014). Therefore, the adaptation concept aims not only to help people and governments deal with the unavoidable adverse effects of climate change, but also to use the new circumstances to improve the living conditions of communities and ecosystems as well as their resilience (GIZ 2019).

3.2 Definitions of maladaptation

Similar to the definition of adaptation, the term maladaptation can semantically refer to an *action* that is counterproductive or detrimental, to the *state* of incompatibility with the environmental circumstances, to the *inability* to respond to disturbances and variations in existing conditions, or to the *process* of functioning less well under a new specific condition (Juhola et al. 2016). In any case, the term refers to the adversity faced by an entity (i.e., ecosystem, economic sector, community, territory, social group, infrastructure or species) or a system under changing conditions. Accordingly, Scheraga and Grambsch (1998) emphasize that maladaptation can be just as harmful as the effects of climate change that a measure is trying to address. They explain that adaptation actions may also have adverse effects if they fail to account for interconnected systems, inadvertently exacerbating risks in other climate-sensitive systems.

Barnett and O'Neill (2010) define maladaptation as "*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*" (p. 88). Based on this definition, the International Initiative on Maladaptation to Climate Change (IMACC) added that maladaptive outcomes undermine the capacity for future adaptation and the willingness to adapt (Bours, Dennis 2014). Broadening that definition, the IPCC's 5 th Assessment Report (2014, p. 20) mentions that such actions may increase the risk of adverse climate-related outcomes or diminish current or future welfare capacity. Similarly, Magnan et al. (2016) have linked the term with a *process* that directly or indirectly increases the vulnerability of the targeted system, external actors, or society, or by creating new drivers of vulnerability and emphasizes the possibility of undermining the capacities and opportunities of future adaptations. In this sense, maladaptation is conceived as a *pathway* (Wise et al. 2014) that an adaptation measure traces towards the detriment of the system's capacity to cope with current and future climate-related effects and environmental changes (Magnan 2014).

The IPCC's Fifth Assessment Report (AR5) included welfare diminishment as a possible maladaptive outcome and Jones et al. (2015) further argued that maladaptation can have significant impacts on broader socio-economic, cultural, and psychological factors that may be related to climate risk, preferring to replace the term welfare with well-being. This perspective is reinforced by Schipper (2020), who expands the definition to the effect that the increase in vulnerability is not only climate-centered, but is also related to many other threats. Thus, even if an adaptation measure can reduce climate risks at the expense of other social goals (e.g., equity, justice, poverty reduction), it can be characterized as maladaptive.

In contrast, Juhola et al., (2016) defined maladaptation as an unintended *result* of an intentional adaptation measure that can also erode the preconditions of sustainable development with the same effects as previously mentioned. This definition aligns with what Brown (2011) and Eriksen and Brown (2011) have described as maladaptation. Magnan et al. (2016) expand on this definition, explaining maladaptation as the *consequence* of an adaptation action that progressively neglects direct and indirect drivers of vulnerability (e.g., social characteristics, cultural values, livelihoods, local economic dynamics, governance systems) across different spatial and temporal scales, with the potential to increase climate risks either to the system (namely people, ecosystem or territory) where it is implemented, or to another interconnected system, or both. Findlater et al. (2021) build on this understanding by indicating maladaptation as a failure of adaptation decision-making, and Jacobson et al. (2019) and Schipper (2020) support this perspective by stating that maladaptation risks will continue to emerge until vulnerability drivers are effectively addressed through adaptation actions.

Building upon the definitions of Scheraga and Grambsch (1998) and Barnett and O'Neill (2010), Granberg and Glover (2014) indistinctly describe the term as all adaptation actions that not only increase the vulnerability to climate effects in the system to which are applied, but also worsen climate change impacts in some other systems. On that note, Atteridge and Remling (2017) and Reckien et al. (2023) conclude that every adaptation option has the potential for both successful adaptation and maladaptation depending on the contextual conditions and the dynamics of the adaptation outcomes across time and space.

It is also necessary to distinguish maladaptation from **failed adaptation** and **simulated adaptation.** While the first refers to an adaptation measure that did not work but whose outcome in terms of vulnerability changes is neutral, the latter describes those actions that give a fake sense of security but neither reduce vulnerability conditions nor build resilience (UNEP 2019). Moreover, maladaptation should not refer to any further consequence or residual risk beyond adaptation limits, as these effects are inherently unavoidable. In the broadest sense, maladaptation is a misconceived adaptation measure that increases risks instead of reducing them.

4 Breaking down maladaptation for a more comprehensive understanding and practical application

Despite the limited investigation of maladaptation, recent literature has advanced in the characterization of causes, "*symptoms*", indicators, and outcomes of maladaptation. Harnessing this progress to better under how maladaptation occurs, we unpacked, disaggregated, and re-arranged the concept into actionable components, namely attributes, forms, mechanisms, drivers, output, and dimensions.

4.1 Maladaptation attributes

Maladaptation involves four attributes (Magnan 2014; Schipper 2020).

- It results from adaptation decisions, including inaction as an adaptation option;
- It brings negative effects in terms of risk levels or well-being;
- It can manifest within or beyond the system or both where the adaptation measures are implemented;
- It can have immediate or delayed effects, even on future generations.

Importantly, an adaptation decision should not be labelled as maladaptive if it is the least harmful course of action available (Jones et al. 2015). This means that an adaptation decision should not be considered maladaptive when it is the best available and reasonable option to appropriately address climate risk under the specific capacities and limitations of the implementation context at a given time, even if it slightly affects risk conditions. That also includes those cases where inaction could be considered as the most adequate response, for example, given poor knowledge of climate risk or very high levels of uncertainty, low institutional and financial capacity to properly implement effective measures at the necessary scale, or the existence of more urgent social issues, priorities, or needs (e.g., hunger, conflicts, healthcare access, housing, water and sanitation).

4.2 Forms of maladaptation

To better understand how maladaptation manifests, it is necessary to expose the different forms in which risk conditions are intensified within a system.

- *Reinforced risk*

The underlying causes of risk, such as vulnerability conditions, are addressed imprecisely and inappropriately, and instead, the adaptation measure exacerbates these or other vulnerability stressors, intensifying the risk conditions in the targeted entity (Juhola et al. 2016; Schipper 2020).

- *Transferred risk*

In this case, the risk conditions are displaced to or intensified on those connected entities that are not targeted by the adaptation measure, while the targeted entity enhances its resilience (Juhola et al. 2016; Atteridge and Remling 2017; Schipper 2020).

- *Propagated risk*

It occurs when the implemented adaptation measure is ineffective and counteractive, affecting in different ways both targeted and non-targeted entities (including future generations), or even the overall system, intensifying risk conditions systemically (Juhola et al. 2016).

- *Induced risk*

This form arises when an intervention compromises other societal objectives at the expense of achieving adaption goals, introducing new threats or exacerbating other risks that were originally irrelevant. It often nullifies, hinders, undermines, competes, or contradicts other dynamics or conditions of the system, aggravating other non-climate-related issues as well as restraining the system's long-term sustainability (Schipper 2020).

4.3 Maladaptive mechanisms

Maladaptation can exacerbate risks (climatic or non-climatic) or trigger new ones in targeted and non-targeted entities or systems, shifting one problem to one or many other problems (Jones et al. 2015). This can unfold in five ways:

- *By increasing exposure*

Exposure is a highly dynamic factor depending on the hazards and their evolution (Lung et al. 2013; Onyango et al. 2016; Parker et al. 2019; Zebisch et al. 2021), as well as the geographical location of entities at a specific time (Oppenheimer et al. 2014; Jurgilevich et al. 2017). It is a risk component that depends not only on changing climatic conditions, but also on a combination of multiple societal factors (e.g., demography, land use). Maladaptive interventions fail to address adaptation needs effectively, and in turn, a system may increase its exposure to a specific climate hazard (Magnan et al. 2016).

- *By increasing sensitivity (social or ecological)*

Sensitivity is not a fixed state. In ecosystems, both climate and social forces affect their structure, composition, and functions, altering environmental conditions and ecological dynamics. In social systems, sensitivity to climate-related stressors results from the feedback of various anthropogenic factors, such as macro-economic dynamics (e.g., supply chains, trading, markets), livelihood dependency, political stability, technological development, demographic composition, governance structures and institutions, access to key resources (food, water, energy) and basic services (primary health care, basic education, public transport, proper sanitation and waste collection). Maladaptation can exacerbate both types of sensitivity (Jacobson et al. 2019) and, consequently, worsen the vulnerability of either the system or specific entities (Magnan et al. 2016).

- *By decreasing adaptive capacity*

Adaptive capacity is determined by economic assets, natural resources, social networks, power structures, agency, rights, institutions, governance modes, human capital, and available knowledge and technology. Maladaptation can weaken or hinder one or multiple of these elements by undermining socio-economic activities and ecological conditions. This results in a reduced ability of the system to prevent, cope, mitigate, or adjust to the changing conditions or benefit from them (Jakku and Lynam 2010; Noble et al. 2014; Atteridge and Remling 2017).

- *By increasing likelihood or severity of hazards*

Hazardous conditions may change when interventions fail to address adaptation needs effectively, increasing the system's exposure to a specific climate hazard (Magnan et al. 2016; UNEP 2019; Chi et al. 2021). Also, several maladaptive interventions often increase the severity of hazards in non-targeted entities or systems by diverting the impacts instead of addressing them (Juhola et al. 2016; Atteridge and Remling 2017; Schipper 2020). Moreover, many maladaptive actions accelerate or result in self-reinforcing feedback loops that alter the return period, timing, rate of change, or patterns of ongoing and future climate hazards, and/or amplify their magnitude, frequency, intensity, extension, and duration (Raymond et al. 2020; Simpson et al. 2021).

- *By introducing other risks in the system*

Maladaptive interventions may introduce other risks to the system or another interconnected system. These can be climatic and non-climatic risks, and they can be induced through changes in the system dynamics, such as unexpected interactions between the response and other system elements, formation of new dependencies, or reinforcement of feedback mechanisms. As a result, maladaptive interventions may foster aggregation and compounding of risks (e.g., drought and food crisis) (Raymond et al. 2020; Simpson et al. 2021), amplification of other stressors (e.g., migration and displacement) (Antwi-Agyei et al. 2018; Jacobson et al. 2019), activation of new threats (e.g., conflicts) (Jacobson et al. 2019; Bertana et al. 2022; Lo et al. 2024), acceleration of emerging risks (e.g., biodiversity loss) (von Döhren and Haase, 2015; Juhola et al. 2016; UNEP 2021; Wu et al. 2021) or substitution of risk conditions (e.g., creation of artificial wetlands for flood control introduces risks of vector-borne diseases) (Campagne et al. 2018; Chi et al. 2021).

4.4 Drivers of maladaptation

To fully understand what is driving maladaptation, it is essential to examine the intervention also as a sub-system subject to the dynamics of the system in which it is embedded and the feedback, interactions, and interdependencies with other system elements. Under that system of systems perspective (Hope 2006; Renn et al. 2022), an adaptation measure can be turned into a maladaptive intervention by exogenous forces, from global to local, as well as endogenous drivers. Thus, to prevent maladaptation, we need to consider the whole range of its direct and indirect drivers (Magnan et al. 2016; Findlater et al. 2021).

The literature (i.e., Tschakert and Dietrich 2010; UNDP 2010; Granberg and Glover 2014; Magnan 2014; Noble et al. 2014; Jones et al. 2015; Magnan et al. 2016; Atteridge and Remling 2017; Campagne et al. 2018; GIZ 2019; UNEP 2019; 2021; Work et al. 2019; Piggott-McKellar et al. 2020; Saunders 2020; Schipper 2020; Wu et al. 2021; Findlater et al. 2021; Glover and Granberg 2021; Bertana et al. 2022; Rahman et al. 2023) reports different economic, environmental, institutional, social, cultural, and technical drivers (also referred to as causes, factors or characteristics) of maladaptive outcomes. Given that these drivers represent several external forces, inadequate planning practices, and mismanagement aspects, we grouped them into three categories (*see* Supplementary Material Table S2):

- *Contextual drivers:* refer to the local socio-economic, environmental, and governance conditions or broader external forces inhibiting a sustainable adaptation process (more in New et al. 2022). These constitute those pre-existing factors and conditions within which the intervention must operate. While the adaptation measure itself cannot control these factors, they may constrain or indirectly influence the design, performance, and implementation of the adaptation action. Examples include social norms, political instability, perceived urgency, or shifting priorities within the local community, as well as macro dynamics of the global system, such as economic shocks, changes in international agreements on climate change, ecological tipping points, and natural climate variability (e.g., ENSO).
- *Structural drivers*: relate to the internal organization, planning, and design of the adaptation measure. These factors refer to how the intervention is structured, the relationship between its components, and the ways to address the risk, representing the core features and endogenous dynamics of the adaptation measure. For example, the failure to account for cross-scale impacts, trade-offs, equity considerations, or system interdependencies.
- *Functional drivers*: represent emergent factors and performance characteristics of the intervention as it interacts and exchanges with the external environment. Although structural or contextual drivers can influence them, these drivers reflect mismanagement decisions contributing to a failed or derailed implementation of adaptation measures. For instance, even a well-designed intervention may lead to maladaptation due to resource maladministration, inadequate stakeholder coordination, or insufficient capacity for monitoring and evaluating its performance over time. In that sense, "*functional*" refers to how the intervention actually works or operates in the real world.

When any of these drivers or the combination of various of them is strong enough to alter either the conditions ("*system's regime*") in which the intervention is taking place or the intervention itself, an adaptation action turns into maladaptive. For example, inherent ecological processes and landscape dynamics in the Mediterranean, together with rural depopulation leading to the abandonment of reforested areas initially designed to cope with droughts and floods, created high-combustibility hotspots, which in turn exacerbated wildfire risks (Ursino and Romano 2014; Jia et al. 2019; Mantero et al. 2020). Another example is the urban greening projects intended to mitigate urban heat island effects and increased temperatures that inadvertently exacerbated social conflicts and inequalities. In many cities, greening initiatives have prioritized economically valuable land and failed to meaningfully engage marginalized communities compounded with other drivers, such as rapid urbanization, intense pressure on land resources, poorly enforced land use regulations, weak governance, and gentrification leading to the displacement of low-income residents, and thus, increasing their vulnerability (Froese and Schilling 2019). This illustrates that maladaptation is rarely due to a single driver but to the dynamic interaction of multiple drivers that can occur simultaneously or sequentially.

4.5 Outputs of maladaptation

Maladaptation can have various impacts on different entities (outputs or ¨*symptoms*¨). The literature highlights numerous instances where an adaptation measure leads to adverse effects, not only for the intended targets but also for non-targeted entities. However, some of these effects may not be explicitly referred to as maladaptive outputs. To derive a general understanding of the information available, it was necessary to analyze the findings from the literature using both deductive and inductive reasoning. To organize them, they were classified into three groups: economic, social, and environmental outputs (*see* Supplementary Material Table S3). As maladaptation outputs behave more as a continuum, it can be more challenging to identify and analyze them in practice. In light of that, this classification underpins the three pillars of sustainability, considering that maladaptation ultimately impairs and threatens sustainable development conditions.

4.6 Dimensions of maladaptation

Maladaptation is multifaceted, affecting environmental, economic, social, cultural, institutional, and political conditions (Magnan 2014). It has different implications for risk and well-being components over time and distinctly affects various entities across space, depending on the interactions and linkages between the maladaptive intervention and other system elements as well as the own system's dynamics and organization. Given that these conditions and interactions are changing dynamically for climatic and non-climatic reasons, detecting when a specific adaptation measure can lead to maladaptive outcomes and its most influential factors is a complex task. The following subsections build on previous works (i.e., Magnan 2014; Jones et al. 2015; Juhola et al. 2016; Magnan et al. 2016; Schipper 2020) and describe the six dimensions that shape maladaptation outcomes.

- *Risk dependency*

Maladaptation negatively affects the propensity to climate risks, as well as other non-climate-related risks (Jones et al. 2015; Schipper 2020), such as violent conflicts, political instability, environmental pollution, and species extinction.

- *Well-being detriment*

Maladaptation has detrimental effects on human well-being (e.g., livelihoods, health, basic needs, cultural identity, sense of belonging, spirituality, community cohesion and other non-economic-valued elements) by eroding societal development conditions (Juhola et al. 2016) and hindering options for sustainable development (Jones et al. 2015; Magnan et al. 2016).

- *Time*

Maladaptation outcomes can take place in different timeframes (Juhola et al. 2016), suddenly or gradually (Magnan 2014; Magnan et al. 2016), impacting current or future generations or both (Jones et al. 2015; Magnan et al. 2016), and their relevance may vary over time according to the changing climatic, environmental, and socio-economic conditions (Jones et al. 2015).

- *Space*

Maladaptation outcomes can extend to areas beyond the geographical boundaries of where the intervention is implemented, reaching ecosystems, communities, or sectors ecologically or socio-economically connected to the target area (Magnan et al. 2016). Subject to the location, the significance of its impacts may be distributed differently across the space (Schipper 2020), as well as their severity.

- *Interconnectedness*

Maladaptation outcomes influence and are influenced by multiple interrelated, interacting, and ever-changing factors of the system (Magnan et al. 2016; Atteridge and Remling 2017; Schipper 2020). Dynamics and components of the system, such as development projects, socio-political processes, economic forces, environmental shocks, technological trends, and global climate variation, may contribute to driving adaptation actions towards maladaptation; similarly, maladaptive outcomes can have significant implications on each of those factors.

- *Receptor-specific*

Maladaptation consequences can affect social groups, communities, territories, ecosystems, species, infrastructure assets, or economic sectors differently (Jones et al. 2015). The degree to which maladaptive outcomes can impact those entities varies according to the receptor's condition (e.g., sensitivity, awareness), capacities, and limitations to deal with them at the moment of their occurrence.

5 Re-defining maladaptation as a point of departure

To make the concept operational, it is necessary to establish a common understanding of maladaptation. To do so, this study proposes a more comprehensive, harmonized, and actionable redefinition of maladaptation, building upon the different interpretations previously described (*see* Sect. 3), including adaptation as the antithesis, as well as from the insights from the conceptual disaggregation of Sect. 4.

> ***"Maladaptation is a process in which the unintended effects of an adaptation decision (including inaction) adversely alter the conditions to anticipate, withstand, manage and respond to risks (climate-related and non-climate-related) and associated impacts in one or various entities (i.e., ecosystem, economic sector, community, territory, social group, infrastructure or species) in relation to the conditions before the decision."***

A key characteristic of maladaptation is that increases vulnerability (incl. sensitivity, susceptibility, or a decrease in adaptive and response capacity), exposure (i.e., geographical location, interconnections, duration, or frequency), or hazard's likelihood or severity (incl. spatial extent, rate of change, timing, intensity, frequency, duration, interconnectedness, or transmission of impacts), exacerbating existing or expected risks or introducing new ones (Fig. 2).

Another characteristic is that maladaptation progressively diminishes the possibilities and probability of success of future adaptation actions while weakening the system's ability to respond, function, and evolve promptly and efficiently in the face of (climatic) disturbances, stressors, disruptions, or abrupt changing conditions (Fig. 3), ultimately leading to system failures.

While maladaptation outcomes are primarily associated with climate-related risks, either sudden extreme events or slow onset processes, they can also influence other risks, such as hazardous natural phenomena, environmental degradation, violent conflicts,

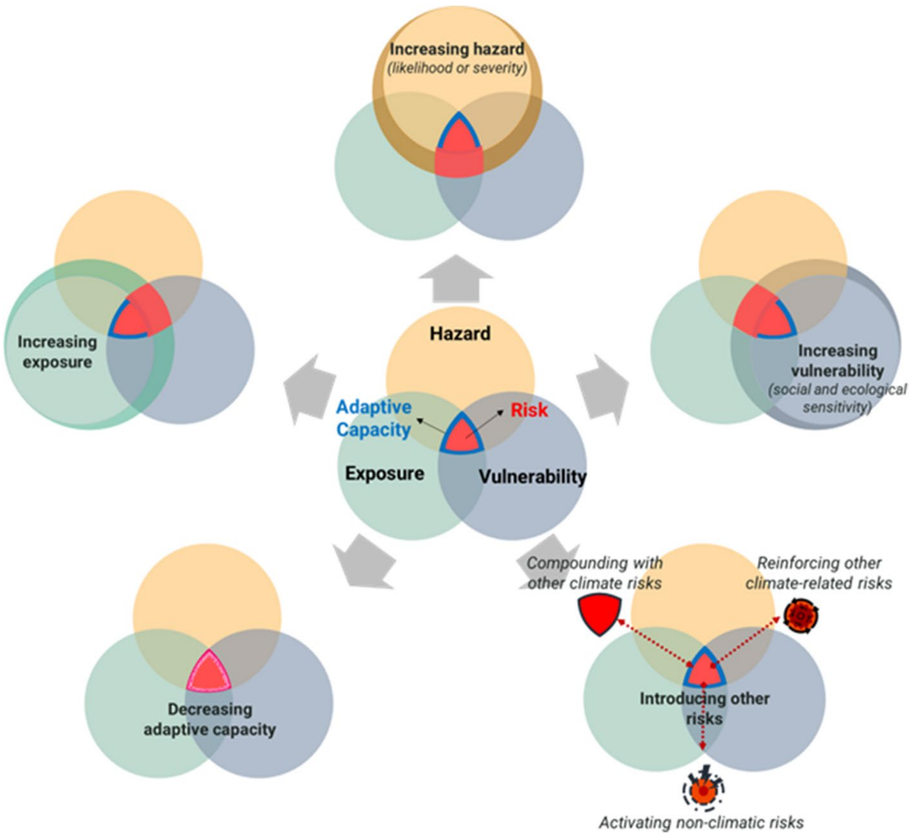

Fig. 2 Effects of maladaptive interventions on risk conditions. Note: Maladaptation can affect risk conditions by either exacerbating one or more components of risk (hazard, exposure, and vulnerability, including adaptive capacity) or introducing new risk conditions (e.g., compounding climate risks through changes in feedback loops or new dependencies between system elements; reinforcing other climate-related risks such as migration and human displacement due to vulnerability amplification; or activating non-climatic risks like conflicts, health issues or biodiversity loss due to unforeseen chain reactions, spillover effects, and systemic interactions)

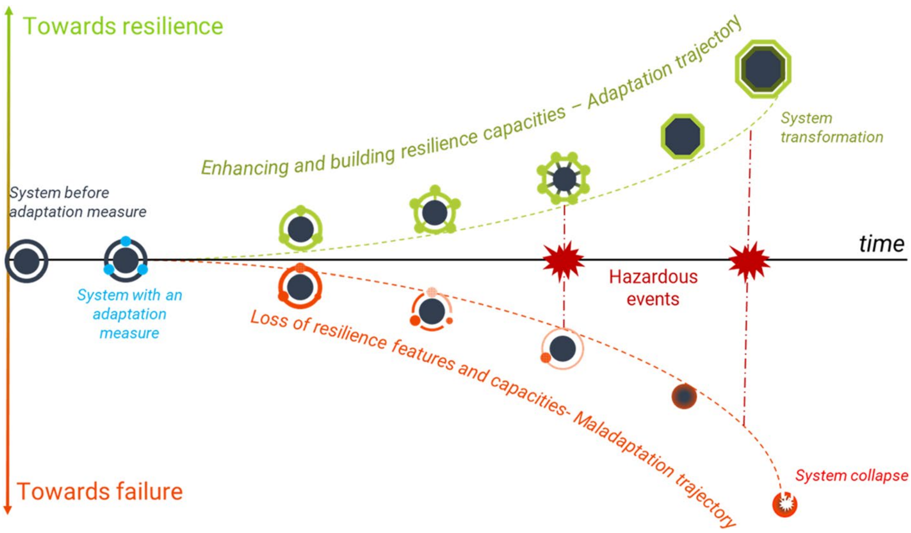

Fig. 3 Maladaptation is a degenerative process that can lead to systemic failure over time. Note: Maladaptation is a deteriorative process wherein a system gradually loses its ability to respond to subsequent hazardous events effectively, thus increasing its risk levels. In contrast to the expected adaptation path of building resilience, the trajectory of a maladaptive response propels the system toward susceptibility, fragility, instability, failure, and ultimately, collapse when a hazardous event strikes

livelihood crises, or economic shocks. This is because maladaptive interventions interact with socio-ecological and economic systems in complex ways and their consequences may accumulate over time or compound with other non-climate-related processes, which, in turn, worsen well-being conditions, undermine sustainable development options, and

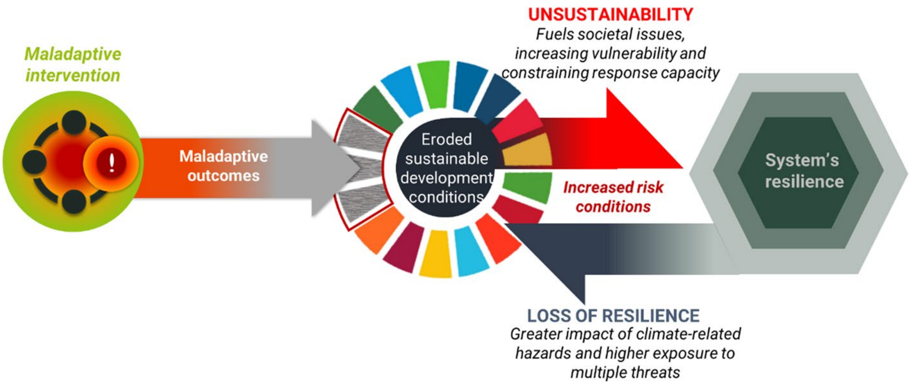

Fig. 4 Maladaptation outcomes and their influence on sustainability and resilience. Note: Consequences of maladaptive interventions can have a negative impact on the both current and future conditions for sustaintable development (directly and indirectly). This can cause societal issues such as poverty, inequality, and environmental degradation to become more pronounced, increasing vulnerability while constraining the system's ability to respond to ongoing and future extreme events. In turn, climate-related hazards have a greater impact on the system while the sytem gets more exposed to other multiple threats, climatic and non-climatic. This creates a vicious cycle were the risk conditions increase progressively as maladaptive outcomes are realized, and climate change and other societal challenges remain unaddressed

compromise ongoing and future opportunities to thrive. Moreover, maladaptation outcomes may manifest at different spatial scales and time frames in a dynamic and interconnected manner, affecting targeted or non-targeted entities, or both, or the broader society, or even future generations. For example, constructing a water reservoir to solve water shortages in one area can have negative impacts on downstream ecosystems and communities due to changes in sedimentation, flooding, nutrient content, and temperature (Lukasiewicz et al. 2013).

Maladaptation outcomes can also affect both resilience and sustainability (Fig. 4). For instance, introducing new crops or diversifying productive activities in response to climate variability (e.g. droughts, increased temperatures, changes in rainfall patterns) can reduce the community's capacity to sustain their livelihoods and cope with future environmental changes if these interventions are not part of their traditional knowledge and past experiences (Zavaleta et al. 2018; Schipper 2020). Concisely, maladaptive interventions and their consequences disrupt and negatively alter the processes and factors that provide the system with its resilience features (i.e., interconnectivity, redundancy, robustness, diversity, flexibility, etc.) by influencing e.g., the criticality of components and functions, the propensity for more failure points, the propagation of cascading failures, or the ability to manage change and uncertainty. This effect can be explained in various ways, such as:

- A reduction of the system's ability to cope with climatic or non-climatic hazards by limiting future responses and adaptation options (i.e., lock-ins and pathway dependency)
- A deterioration of the system's capacity to withstand future disturbances or shocks by increasing its sensitivity, e.g., to environmental degradation.
- An increase in the system's requirements to normally operate by worsening vulnerability conditions or introducing new drivers of vulnerability (e.g., resource depletion, infrastructure damage, and biodiversity reductions).
- Weakening the system's stability and recoverability by increasing the exposure to existing or new hazards.
- Inducing irreversible changes (i.e., tipping points), for instance, through accelerated ecosystem degradation mechanisms, exacerbating non-climate related historical processes like inequitable resource distribution or socio-political conflicts, or driving positive climatic feedback loops.

Furthermore, maladaptive interventions can undermine specified or general resilience, considering that their outcomes affect the conditions of a particular risk, a few of them, or the overall risks in the system (Magnan et al. 2016). As explained above, maladaptation may exacerbate climate risks (targeted and non-targeted), as well as induce non-climate-related ones that were nonexistent or negligible in the original conditions. Hence, maladaptation can have three possible detrimental *directions*:

a. When affects specific climate resilience to the targeted risk(s),
b. When affects general climate resilience to non-targeted risk(s),
c. When affects the overall system's resilience by introducing or triggering new non-climatic risk conditions.

Given the complex interactions and dynamics within the system and between the system and other systems, maladaptive interventions may also generate developmental trade-offs and exacerbate other societal problems, such as poverty, inequity, conflicts, displacement, pollution, biodiversity loss, and water and food insecurity. Thus, in terms of sustainability, maladaptation can erode well-being and sustainable development conditions by e.g., harming livelihoods, human health, culture, social structures, and basic needs provision, among others (Jones et al. 2015; Tendall et al. 2015; UNEP 2021). This causes a vicious cycle consisting of an accelerated, positive, degrading feedback loop, in which an entity or the broader system is gradually becoming less able to operate and face the changing conditions. As the system loses resilience over time, the severity and likelihood of shocks, disruptions, and disastrous events amplify. This, in turn, affects the system's development conditions negatively and increases the sustainability gaps, which feed back to the system's vulnerability and inability to effectively respond to the changing climate and other threats.

In essence, maladaptation shrinks both "hard" and "soft" adaptation limits while augmenting the potential for unavoidable losses and damages. Thus, maladaptive outcomes should not be considered residual risks from the adaptation measure; rather, the intervention itself becomes a risk, an amplifier, or a driver of risks.

6 A practical framework for an ex-ante analysis of maladaptation

As described above, operationalizing the maladaptation concept is a pending task in adaptation planning. Major progress on this task has been hindered by not only the lack of clarity on the concept and the difficulty in assessing adverse effects of adaptation actions quantitatively and qualitatively, but also the low development of pragmatic approaches to analyze maladaptation risks and their multifaceted and dynamic nature—particularly in ex-ante or prospective way. Numerous publications explicitly encourage practitioners to prevent adverse effects of adaptation measures, however, without guiding them to an early identification or exploratory analysis. While a variety of guidelines, safeguards and principles for effective adaptation exist, they fail to provide a methodology to explore, diagnose, and correct maladaptive interventions. Using the conceptual breakdown of maladaptation, we propose a systematic approach to analyze current and future risks of maladaptation in a practical way (Fig. 5).

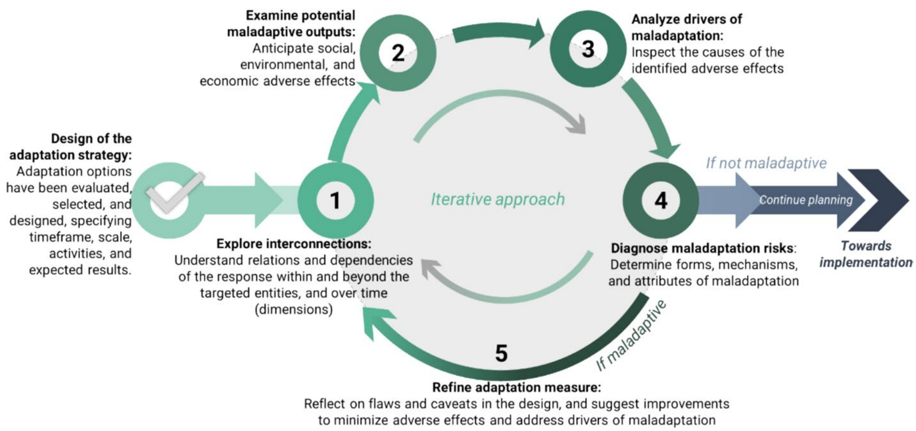

Fig. 5 Practical framework for analyzing maladaptation

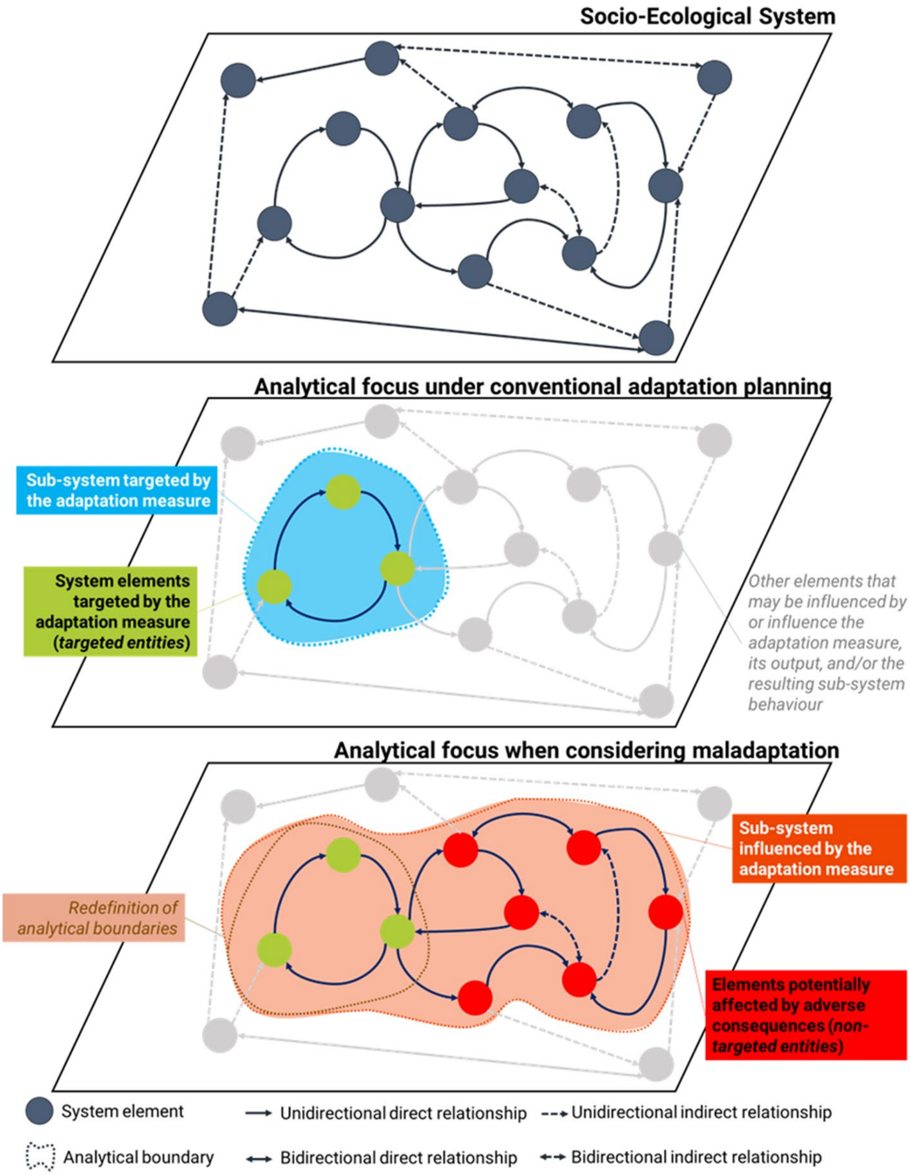

Fig. 6 The analytical focus on maladaptation accounts for the system's complexity. Note: In adaptation planning, the conventional approach focuses solely on the target elements of the system (targeted entities). This approach often leads to adaptation measures being viewed as isolated, independent sub-systems without considering the complex and dynamic interconnections of elements of socio-ecological systems. However, by considering the concept of maladaptation, the analytical boundaries broaden due to existing or emerging interdependencies. This entails looking at the potential negative consequences of adaptation measures not only on the targeted entities but also in other system elements beyond the direct influence boundaries. By broadening the analysis, decision-makers can better understand the potential ripple effects of adaptation measures and make more informed and comprehensive decisions, thereby increasing the success of the adaptation process

The framework integrates the six components of maladaptation—dimensions, outputs, drivers, attributes, mechanisms, and forms— and is structured into five analytical steps, each crucial for examining the risk of maladaptation and, thus, refining the adaptation measures. In contrast to the conventional adaptation planning approach that focuses on the targeted entity, the framework proactively expands the boundaries of analysis of the effects of adaptation responses (Fig. 6). It begins with a comprehensive exploration of the interrelationships and dependencies of the intervention within the targeted entities and other system elements *(interconnectedness dimension),* as well as how these interactions may change in current and future settings (step 1). To effectively analyze maladaptation, spatial and temporal scales should be determined based on the system's interconnectivity and the timespan of the respective adaptation measure under analysis. The spatial scope (*space dimension*) is determined by analyzing the interdependencies between the **targeted entities** (i.e., territory, ecosystems, sectors, infrastructure, communities or social groups related to where the adaptation measure is intended to be implemented and where its associated benefits and outcomes are expected to be delivered) and other interconnected system elements that may not have been initially considered during adaptation planning, referred to as **non-targeted entities**. For instance, the spatial scope should extend beyond the immediate intervention area to include downstream territories, surrounding ecosystems, neighboring communities, or interconnected sectors potentially affected by cascading effects. These interdependencies can reveal specific receptor entities that may be affected directly, indirectly, and differentially by the adaptation measure (*receptor-specific dimension*). While defining these boundaries can be somewhat arbitrary, it is crucial to recognize that an adaptation measure may have an effect beyond the targeted entities or system. Importantly, the spatial scope may change over time and with it, the potential receptors of maladaptive outcomes. This is because interactions and interdependencies among system elements may change as the adaptation measure develops. Similarly, temporal scales (*time dimension*) should reflect both immediate and long-term effects, acknowledging that some maladaptive outcomes might not manifest until decades after implementation, but their causes may be due to considerations or decisions over time. This requires examining the different phases of the adaptation measure's lifecycle (i.e., inception, establishment or construction, operation or implementation, and maintenance). Doing so ensures that maladaptation aspects are analyzed across different timeframes and with an analytical boundary broader than the initially considered in the subsequent steps.

Next, the framework examines potential adverse effects (**maladaptation outputs**), focusing on the observable consequences of adaptation measures and their significance to the affected entity (step 2). This may include assessing the likelihood, magnitude, scale, severity, duration, and time of emergence of social, economic and environmental impacts, as well as how these effects might aggregate, accumulate, or compound with other processes in the system (*due to well-being detriment dimension*). This sets the foundation for a deeper analysis of the **drivers of maladaptation** – potential contextual, structural and functional factors leading to the identified adverse effects (step 3). Subsequently, diagnosing maladaptation risks (step 4) represents a decision point in the framework. This step consists of determining whether the current design of the adaptation measure might be considered maladaptive (**maladaptation attributes**) and identifying potential **forms** and **mechanisms of maladaptation** (*consistently with the risk-dependency dimension*). The estimation of changes in risk conditions can be achieved by comparing pre- and post-intervention scenarios, as well as evaluating different adaptation options, including inaction. Determining whether an impact is "slight" or "significant" requires context-specific thresholds, which could be established based on e.g., baseline data, stakeholder input, and scenario analysis. The weighing of these impacts on specific receptors, regardless are short- or long-term impacts, should adopt a justice and equity lens to examine the distribution of risks and benefits across the system, ensuring that no entity is disproportionately burdened. Incorporating these considerations in the planning allows practitioners to undertake adaptation actions that are both equitable and fair. If, through these comparisons, the selected adaptation measure emerges as the best and most reasonable option—because it has the lowest adverse impact on risk conditions—then it should not be considered maladaptive. This acknowledges that adaptation actions, like any other human intervention, inevitably involves trade-offs and potential adverse effects and, in some contexts, these may be unavoidable due to the local capacities and conditions for adaptation. If the intervention is not maladaptive, the process moves towards the last part of the planning phase and implementation. Otherwise, it undergoes systematic refinement (step 5), using insights from earlier steps. Insights from Step 1 are used to ensure that the multi-faceted and complex nature of maladaptation is well integrated. Outputs identified in Step 2 inform what adverse consequences need to be minimized. While drivers analyzed in Step 3 help identify those factors that need to be addressed or prevented, the mechanisms and forms diagnosed in Step 4 guide the design of targeted amendments that can mitigate the materialization of maladaptation risks. In cases where an intervention indicates potential significant impacts—such as when the harms to one or more entities outweigh the benefits to others—is necessary to modify its design, integrate counterbalanced measures, or reassess alternative options, including inaction.

After refinement, the intervention initiates an iteration to verify that this new version is indeed mitigating the risk of maladaptation. As proposed, the analysis of maladaptation risks is embedded in the planning cycle, specifically after conceiving and selecting options to address the specified climate risk, but before moving towards the implementation phase. This allows for repeated revisions and enhancements of adaptation measures, thereby helping practitioners prepare more effective, and sustainable interventions while increasing their chances of success.

To illustrate the framework's application, consider a hypothetical coastal defense project designed to mitigate the impacts of sea-level rise on an island. In Step 1, the analysis of interdependencies identifies the infrastructure and adjacent community as targeted entities while surrounding ecosystems (e.g., mangrove, coral reefs, and dunes), communities from neighboring islands, and tourism and fishery sectors as non-targeted entities. These are all interrelated given the marine currents and sediment flows, which the adaptation measure disrupts at different timeframes: first, coral reefs and fisher communities during the construction, and second, tourism and nearby mangroves and coastal dunes in the operation. In Step 2, potential maladaptive outputs are identified, such as loss of terrestrial and marine habitats, reduced beach access for livelihoods, disruption of the fishery and tourism value chains, and intensification of inequality and migration. Step 3 examines the drivers that are leading to these adverse effects. Those involve contextual conditions like funds that do not support long-lasting adaptation processes, clientelism, and social and political preference for immediate results over long-term benefits; structural factors like failure to encompass cascading effects and trade-offs, neglection of local livelihoods, and creating path dependency; and functional drivers such as degradation of coral reefs, mangrove forests, and coastal dunes, as well as reduced fishery productivity, diminished tourism revenue, and low engagement of multiple actors. In Step 4, maladaptation risks are diagnosed by identifying attributes (i.e., (i) an adaptation measure that (ii) brings negative effects (iii) within and beyond the system and (iv) have immediate and long-term impacts), mechanisms (e.g., reduced adaptive capacity due to loss of ecosystems, increased vulnerability of adjacent communities, increased sensitivity of tourism sector), and forms (e.g., reinforced risks in fisheries, transferred risks to nearby communities). Finally, in Step 5, the adaptation measure is refined by integrating complementary measures like dune and mangrove restoration, and engaging stakeholders to address equity concerns. After additional iterations, the design of the adaptation measure is further improved using permeable walls in combination with artificial reefs to reduce sediment flow disruption and erosion downstream. In that way, the adaptation project minimizes maladaptation risks while ensuring effective resilience building and long-term sustainability for both targeted and not-targeted entities.

7 Discussion

Many authors have contributed to the understanding of specific aspects of maladaptation in-depth but in a fragmented way. This can lower the transferability of related knowledge from science to practice, and hence, its applicability in adaptation planning. To consolidate that knowledge, we reviewed and dissected the concept of maladaptation into analytical elements such as attributes, forms, mechanisms, drivers, outputs, and dimensions. In our view, these results can help understand maladaptation in an integrated way and stimulate the development of analytical tools that can proactively enhance the design, implementation and monitoring of adaptation actions by preventing maladaptation risks.

As there is neither agreement on the definition nor a widely accepted conceptual framework, we propose a harmonized, integrative, and expanded definition of maladaptation. With this new definition, we aim to overcome the debate of what falls under maladaptation and what does not and, instead, focus scientific and empirical efforts on how to make the concept operational and valuable for preventing maladaptation risks in real-world applications. As Findlater et al. (2021) noted, systematic analysis of maladaptation is restricted by narrow definitions and conceptualizations that neglect the relevant processes and outcomes. Rather than labelling an adaptation option as maladaptive, a comprehensive and clear definition of maladaptation can allow the scientific debate to progress beyond the terminology and focus on the core of the issue, which is how maladaptation may arise and how to prevent it. We sustain that consolidating a definition can help practitioners recognize *signs* and *symptoms* of maladaptation and define key parameters for better design adaptation measures. Therefore, we encourage the adaptation community to embrace the proposed definition of maladaptation and keep evolving our understanding through real-world examples.

Regarding the introduced framework for identifying and preventing maladaptation risks at an early stage, we also uphold its practicality and potential usefulness for practitioners. Examples from the literature across its five analytical steps illustrate the framework's applicability for not only examining maladaptation but also ways to improve the design and implementation of adaptation measures. In *Step 1—Explore interconnections*, Di Baldassarre et al. (2018) broadened the analytical scope of an adaptation measure (specifically, the expansion of reservoirs to address droughts) by examining its dependencies with water supply and demand cycles and their relationship with the vulnerability of some economic sectors in case studies from Australia and Greece. Similarly, Wiréhn et al. (2020) investigated the broader implications of agricultural adaptation measures in Finland and Sweden by assessing the direct effects of adaptation decision-making on socio-ecological aspects and the interacting factors within these systems. Kirshen et al.

(2008) also analyzed the interdependencies among infrastructure systems in Metropolitan Boston, USA, focusing on how adaptation actions in one sector impact others. In *Step 2- Assessing maladaptive outputs*, Tubi and Williams (2021) explored the major maladaptive effects of large-scale water desalination, which include increased energy demand and subsequent distortions in energy prices, as well as associated greenhouse gas emissions. They noted that such measures could lock societies into an energy-intensive development pathway while making critical infrastructure more vulnerable to risks associated with sea-level rise. Similarly, Neset et al. (2019) analyzed maladaptive outputs, such as increased competition over water resources and the degradation of wetlands due to the use of agrochemicals and nutrient leakage, arising from agricultural adaptation measures like shifting to new crop varieties, developing irrigation systems, and improving drainage in Sweden and Finland. Antwi-Agyei et al. (2018) studied how smallholder farmers in Ghana adopted various adaptation strategies, including extensification and intensification of agriculture, temporary migration, planting drought-resistant varieties, irrigation, and livelihood diversification, to confront erratic rainfall, high temperatures, floods, and droughts. Their study revealed several associated maladaptive outputs, such as increased greenhouse gas emissions due to heightened pesticide use, deforestation, increased pressure on social services in neighboring regions, and worsening conflicts related to water use. Through a different approach, Suckall et al. (2014) examined how adaptation strategies in Zanzibar, Tanzania, present trade-offs with mitigation efforts, developmental goals, and long-term adaptation strategies by leading to higher carbon pathways, increased conflicts between villages and among resource users, and to the depletion of natural resources, respectively –an approach also highlighted by Adger et al. (2007). In *Step 3 – Identification of drivers of maladaptation*, several examples illustrate this analysis. For instance, Torabi et al. (2023) found that the conversion to agritourism as an adaptation strategy in Iran's agricultural sector unintentionally increased vulnerabilities. This was driven by inadequate government support, legal gaps, and a lack of empowerment. Similarly, Zavaleta et al. (2018) revealed that a combination of population growth, resource degradation, and governmental policies contributed to the heightened vulnerability (to climatic and other stressors) of Indigenous communities in the Peruvian Amazon. Also, Piggott-McKellar et al. (2020) identified that poorly structurally designed seawalls in Fiji have exacerbated coastal stressors in nearby communities. Additionally, Clarke and Murphy (2023) examined how contextual factors, such as place-based values, perceptions of climate impacts, past failed adaptation efforts, and trust in the authorities responsible for adaptation planning, can lead communities in Dublin, Ireland, to resist flood defense projects. This resistance creates lock-ins that further exacerbate vulnerabilities and limit future adaptation options. In addition to the examples mentioned above (i.e., Piggott-McKellar et al. 2020; Neset et al. 2019; Tubi and Williams 2021; Antwi-Agyei et al. 2018; Torabi et al. 2023; Zavaleta et al. 2018), the studies of Asare-Nuamah et al. (2021) and Chi et al. (2020) illustrate *Step 4 – Diagnose maladaptation risks*. The former described how agricultural adaptation measures in Ghana, such as agrochemical use, manifest different forms of maladaptation by affecting risk conditions in both targeted actors (smallholder farmers) and non-targeted entities (ecosystems, external farms, water users), as well as in the broader system through GHG emissions, degradation of water bodies, and impacts on human health. Chi et al. (2020) examined adaptation measures, such as dikes, pump stations and detention ponds, reinforced risks related to heavy rainfall and land subsidence in Taiwan by increasing exposure and sensitivity of both the targeted and non-targeted entities. Additionally, Biella et al. (2024) categorized maladaptive interventions into "fixes that fail," "band-aid solutions," and "success for the successful", using a system archetypes approach—an innovative lens that merits further exploration. In *Step 5 -Refine adaptation measure*, all the studies mentioned above resulted in recommendations and concrete actions to improve the analyzed adaptation measures. By learning from these examples and building on their applied methods and tools, we demonstrate the potential applicability of the framework in identifying, assessing, and addressing maladaptation risks across varied adaptation contexts.

From that perspective, the proposed framework offers another approach to evaluating the feasibility (i.e., *whether an adaptation measure can operate efficiently and sustainably over the long term*), viability (i.e., *the capability of an adaptation measure to deliver adaptation and resilience benefits that effectively address identified risks*), and suitability (*appropriateness of adaptation measure given the local conditions and dynamics*) of the adaptation measure. Accordingly, it examines relevant aspects such as *what might be adverse about adaptation actions, to whom* and *in which ways*, *when* and *where*, *what might be driving it*, *how adverse effects might evolve and end up in terms of risks*, and *how to avoid that to happen.* With this additional ex-ante analysis, we argue the significance of our work. Particularly, considering that none of the publications translates scientific knowledge into a systematic way to analyze maladaptation comprehensively, apart from the framework presented by Reckien et al. (2023), which is not exclusively designed to prevent maladaptation but to evaluate the outcome of adaption actions. Thus, we address this gap, providing researchers and practitioners with an approach to comprehensively examine the occurrence of maladaptation, from their emergence and manifestation to their ultimate impacts on the system's resilience and long-term sustainability.

Fully capturing the complexity and dynamics of socio-ecological systems is neither analytically feasible nor practical. The interconnectedness of the systems often involves countless variables, feedbacks, and uncertainties that cannot be entirely accounted for in a single analysis. Instead, the framework offers a structured approach to analyzing the most significant and influential interactions, allowing practitioners to prioritize and address key maladaptive features. It focuses on these critical linkages and processes aiming to ensure relevance and applicability to real-world adaptation actions. Hence, what could be debatable as a limitation, is from our view a balanced approach between practical value and analytical rigor.

While the proposed framework focuses on ex-ante analysis, integrating and adapting a similar analytical approach in the Monitoring and Evaluation (M&E) can help understand the success of adaptation measures. By doing so, practitioners can reassess the assumptions regarding drivers and potential maladaptive effects identified during planning stages, detect unexpected adverse consequences throughout the lifespan of adaptation actions, update the analysis according to the changing conditions (i.e., climate, ecological, socio-economic, knowledge, technological, and political), and refine the intervention based on the observed performance and outcomes. Extending and adjusting this framework to the M&E ensures that the adaptation measure remains responsive to emerging risks while contributing to maximising positive adaptation outcomes across the system.

We stress the need to incorporate the analysis of maladaptive interactions between existing adaptation measures in place and future adaptation actions during the identification, appraisal, and selection of adaptation options. In that line, we also propose that climate risk analysts integrate the maladaptive potential of past or current interventions into the assessment of ongoing and future climate-related risks. This is in line with Simpson et al. (2021) and the future directions of climate risk assessment as envisioned by the IPCC (2022). Furthermore, we encourage the adaptation community to test our suggested approach in different contexts, with various types of adaptation measures and at different stages (e.g., design, inception, initial implementation). This will help not only improve the framework outlined in this article but also gather evidence and knowledge about maladaptation while contributing to planning future adaptation actions better.

We acknowledge that the three outputs of this study, namely new definition, conceptual breakdown, and practical framework, may not be a definitive version but an iteration of the process towards a full understanding of maladaptation. Nevertheless, we also recognize the practical and scientific value of these outputs in analyzing maladaptation risks. These three developments seek to provide the basis for future research to keep improving the understanding of maladaptation, as well as support research on adaptation effectiveness (see New et al. 2022). Thus, we recommend building upon them in future studies.

8 Conclusions

This research aimed to investigate how practitioners can avoid the risks of maladaptation by presenting a pragmatic understanding of maladaptation that can address gaps in the science-practice interface. It started with an exploration of the definition of maladaptation, gathering various perspectives on the subject and its conceptual development in the literature. The growing number of recent studies and the ongoing debate about the term demonstrate that it is becoming more evident and frequent in practice, and thus, an urgent issue to address in the climate adaptation community. In this regard, the study addressed three key elements crucial to examining maladaptation.

Firstly, the study broke down the concept of maladaptation into analytical elements such as attributes, forms, mechanisms, drivers, outputs, and dimensions. This provides a basis for researchers and practitioners to develop analytical tools that can improve the planning and implementation of future adaptation actions.

Secondly, the paper redefined maladaptation by reconciling existing definitions and knowledge on the subject to improve its understanding and operationalization. We sustain that the proposed new definition is comprehensive, scientifically sound, and clear enough to encourage practitioners to include it in current and future adaptation planning processes.

Thirdly, the study presented a practical framework that includes the maladaptation risk lens in the project cycle of adaptation measures, aiming to enhance the effectiveness and sustainability of adaptation processes. Its systematic, cohesive, and easy-to-understand approach to analysing maladaptation risks not only seeks to improve the design of adaptation measures and support the decision-making process but, overall, to maximize the adaptation benefits and outcomes. By making practitioners aware that adaptation actions can also counter adaptation goals and other societal priorities with inadvertent side-effects, the risk of maladaptation can start being considered more carefully in the entire decision-making cycle.

Adaptation is no longer an option but a necessity for development and a collective quest in which we cannot fail. Without understanding and reflecting on how maladaptation happens, it will be challenging to properly design and implement effective adaptation measures. With the increasing investment in climate adaptation worldwide, the maladaptation lens is an opportunity to advance towards low-regret actions and prevent those solutions of today from becoming the hazards of tomorrow.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11027-025-10217-w.

Author contribution OHR was responsible for study conception and design, material preparation, data collection and analysis, writing and original draft preparation. YW has reviewed and discussed the scientific content and contributed to editing. UN contributed to the study conception and design, editing, reviewing and scientific discussion, and supervised the production of the final version. All authors commented on previous versions of the manuscript and read and approved the final manuscript.

Funding Open access funding provided by International Institute for Applied Systems Analysis (IIASA). The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Data availability No datasets were generated or analyzed during the current study.

Code availability Not applicable.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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