Adaptation pathways for effective responses to climate change risks

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Adaptation pathways for effective responses to climate change risks

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Abstract

Climate related changes are already affecting every area of our world and will increasingly do so as global warming increases, resulting in compounding and cascading risks across multiple locations and sectors. Deliberative processes and anticipatory actions are required to adapt to the associated complex and uncertain systemic risks, with dynamic and long-term planning needed even where there is limited knowledge of the effectiveness of adaptation. In this focus article, we examine the adaptation pathways developed for the Europe Chapter of the IPCC AR6. We argue that illustrative pathways built on quantitative and qualitative assessment of adaptation effectiveness can inform adaptation planning to manage the increasing severity of risks. We find that as the global warming level increases adaptation pathways can diverge, leading to radically different futures, for example, adaptation responses to sea level rise. We illustrate how adaptation measures for different risks interact resulting in trade-offs, for example, increasing water scarcity. Although pathways offer a useful framework to address multiple adaptation challenges, other supporting conditions are needed for the successful implementation of adaptation, such as establishing legitimacy and buy-in through collaboration of various actors and effective governance. Ultimately, adaptation will be increasingly more complex and constrained in a warmer world, increasing risks of losses and damages to people and nature.

This article is categorized under:
Vulnerability and Adaptation to Climate Change > Institutions for Adaptation
The Social Status of Climate Change Knowledge > Climate Science and Decision Making
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KEYWORDS
adaptation pathways, climate risks, decision making, warming levels

1 | INTRODUCTION

Climate change is posing risks to humans and ecosystems which accelerate as global warming increases (IPCC, 2022a). Extreme events such as the exceptionally hot and dry spring/summer of 2018 in the Northern Hemisphere, the unprecedented Western North America heatwave, and the Western Europe flood of 2021 and their impacts give an indication of some of the challenges ahead (Apel et al., 2022; Vogel et al., 2019). There has been an increasing recognition of the complexities of climate impacts and the compound and cascading nature of climate hazards and risks (Raymond, Horton, et al., 2020; Simpson et al., 2021; Zscheischler, Martius, Westra, Bevacqua, & Raymond, 2020). In the summer of 2022, compound dry extremes of heat, drought, and fire affected Europe, while early heat onset had devastating consequences in India and Pakistan. Heat and dry extremes had been followed by torrential rain and powerful storms, which led to heat-related human deaths (Zachariah et al., 2022). Record-breaking monsoonal rainfall in 2022 led to landslides and floods in Pakistan which resulted in thousands of lives lost and many more affected, as well as incommensurable damages to local communities and infrastructures (Zachariah et al., 2022). Many of these extreme climates have been repeated in 2023, with heatwaves on land and in the ocean, wildfires, floods, and droughts (Zachariah et al., 2023). Increasingly these events have been attributed to anthropogenic climate change (Philip et al., 2020).

Alongside these sudden events, slow onset changes due to increasing heat on land and in the ocean (Lenoir et al., 2020; Smale et al., 2019) have altered our natural ecosystems and caused local extinctions as well as losses in important staple foods (Mbow et al., 2019). Glaciers have been retreating at a rate that is unprecedented in the least 2000 years affecting runoff and sea level, with sea levels having risen by approximately 0.20 m between 1901 and 2018 (Fox-Kemper et al., 2021). Knowledge of climate change and climate risks has rapidly progressed in the past decade, with a growing number of case studies, longer time series analysis, sophisticated modeling, experiments, and mechanistic understanding assessing current and projected impacts under alternative scenarios (Martínez-Solanas et al., 2021; O'Neill et al., 2016; Tabari et al., 2021; Tittensor et al., 2021).

Adaptation measures have been implemented in response to these increased threats (Berrang-Ford et al., 2021) supported by increased risk knowledge and impact awareness (Archibald & Butt, 2018). Adaptation modeling has informed decision making, highlighting where actions are most urgently needed (Kondrup et al., 2022). These advances have allowed a move from adaptation strategies and plans to implementation and, in some cases, to monitoring of adaptation (Leiter, 2021). Yet, the shifting frequency and magnitude of climate change impacts, the interconnectedness of many events, and their cascading consequences are increasingly challenging adaptation plans and actions (Simpson et al., 2023), creating a growing adaptation gap, that is, the difference between adaptation needs and adaptation actions (Garschagen et al., 2021). Inadequate knowledge and uncertainties about future effectiveness of adaptation responses challenge our ability to reduce projected risks under rising temperatures (Berrang-Ford et al., 2021). Regular reporting and monitoring of adaptation can help overcome uncertainties and to factor in new knowledge as it becomes available. Still, not every change can be monitored, not all needs are considered, and often long-term monitoring is not built into policy programs. Furthermore, for certain systems like terrestrial, marine, and freshwater ecosystems, we know more about the limits of adaptation than the effectiveness of their adaptation options (Jankowska et al., 2022; Morecroft et al., 2019).

Studies on impacts and adaptation have, to date, mostly explored risks for a specific location or moment in time (e.g., mid-century; Rohat et al., 2019; Viviroli et al., 2020), selected scenarios (O'Neill et al., 2020), and adaptation options (Tamura et al., 2019). The interaction among multiple risks, their respective adaptation responses, and dynamic nature have largely been neglected in adaptation modeling and planning, thereby potentially overestimating the effectiveness of adaptation measures and the extent of residual risks (Magnan et al., 2021; Simpson, Mach, Constable, Hess, Hogarth, Howden, Lawrence, Lempert, Muccione, Mackey, New, et al., 2021). Furthermore, climate warming interacts with socio-economic developments and behavioral changes which jointly influence adaptation effectiveness, creating local challenges and opportunities that might not be fully anticipated (Haasnoot et al., 2020).

All this poses significant challenges for decision makers when trying to adapt to (i) future climate risks of unprecedented magnitude and/or frequency; (ii) multiple climate risks in the same region/location, including compound and cascading events; (iii) climate risks with significant long-term impacts; and (iv) climate risks for which there is limited knowledge on the effectiveness of adaptation options. Here, we argue that risks and adaptation interactions need to be considered together, over time, for different levels of warming and accounting for local or regional contexts. We use illustrative adaptation pathways, based on the key risks and adaptation effectiveness assessments developed in the IPCC WG2 Europe chapter, hereafter Europe chapter (Bednar-Friedl et al., 2022a), as a framework to unpack these challenges. We provided examples and reflections on how illustrative adaptation pathways can define solutions to manage projected key climate risks in the context of deep uncertainty about the scale of the impacts, the effectiveness of the adaptation action, and how the policy context may change through time and between jurisdictions.

2 | A COMBINATION OF KEY RISKS AND ADAPTATION PATHWAYS

The assessment of key risks due to climate change in the IPCC is based on expert judgment and elicitation (Zommers et al., 2020). These key risks have been instrumental in drawing attention to the most severe global and regional risks (Magnan et al., 2021). The criteria that define key risks are risk magnitude and likelihood of occurrence, timing (i.e., the time frame or period during which the risks are expected to occur or manifest), and the ability to address the risks through adaptation (O'Neill et al., 2022). The burning ember diagrams that accompany these key risks display the increasing risk with increasing global warming levels (GWL) and the confidence in risk transitions (Zommers et al., 2020). The burning embers diagrams have helped to visualize key risks accrual and are widely used to communicate political urgency (O'Neill et al., 2017). The transitions in the diagram are not linked to a specific scenario but rather a GWL and, therefore, they could occur at different times across the next decades.

In the sixth assessment cycle of the IPCC (AR6), the key risks were assessed to show risk reduction through adaptation and mitigation and to highlight the presence of residual risks (Magnan et al., 2021). The synthetic chapter, "Chapter 16—Key risks across Sectors and Regions", of the AR6 WGII differentiates between low adaptation, as a continuation of today's actions, and high adaptation, as adaptation has reached its maximum potential (O'Neill et al., 2022). While this consideration of potential adaptation is useful to show the need for upscaling adaptation, the separation into discrete states does not consider adaptation as a dynamic process.

Adaptation pathways are a complementary approach to the burning ember diagrams because they can guide flexible decision-making as risks change through time (Werners et al., 2021). Adaptation pathways provide insights on the timing, path-dependency, and limits of combinations of adaptation options, to support longer-term and robust decision making (Haasnoot et al., 2013; Hermans et al., 2017). These pathways support decision making under conditions of deep uncertainty as opposed to a management of risks after they materialized (Marchau et al., 2019). Such pathways have previously supported the design of strategies in flood management (Haasnoot et al., 2019; Hall et al., 2019), winter tourism (Vaghefi et al., 2021), and water resource management (Haasnoot et al., 2012). By incorporating a wide range of practitioner expertise and local experience, the adaptation pathways draw on a wide range of knowledge and reveal adaptation challenges and gaps (Werners et al., 2021).

In the IPCC AR6 WGII assessment for the Europe Chapter, the key risk assessment was linked with respective adaptation measures and effectiveness under different warming scenarios from the scientific literature to build the illustrative adaptation pathways. The literature covers both near-term action to low warming levels and longer-term and often more transformative actions, but also more speculative assessments, under higher warming levels. Low warming corresponds to future conditions that are in line with 1.5°C pathways, medium warming refers to conditions consistent with warming up to 2.5°C, and high warming above 2.5°C (IPCC, 2021; O'Neill et al., 2022).

The key risks identified for Europe as part of the Europe chapter comprise (1) the impacts of heat on humans and on natural systems (KR1), (2) the impacts of heat and drought on crop production (KR2), (3) the risk of water scarcity (KR3), and (4) the risks of pluvial, riverine and coastal flooding (KR4). Details of this assessment are provided in Box 1 and extensively explained in the supplementary material of the corresponding Europe Chapter (Bednar-Friedl et al., 2022b).

Using the Europe-focused literature collected in the Global Adaptation Mapping Initiative (GAMI; Berrang-Ford et al., 2021) complemented by literature searches performed by the lead authors and contributing author team of the Europe Chapter, we synthetized knowledge on adaptation options and their risk reduction potential (hereafter effectiveness). The GAMI assessment is a global effort to systematically collect and assess the evidence on empirical adaptation. The analysis concentrated on studies that provide empirical evidence on adaptation effectiveness, thereby excluding opinion, method, and theoretical studies. Effectiveness is assessed following a scoring system that assigns low, medium, and high effectiveness to an adaptation response depending on the level of risk reduction described in the corresponding study and then averaging the results across all studies. The main aspects of each key risk, adaptation options, and some key characteristics, trade-offs, and synergies that have emerged from the assessment in Chapter 13 and the associated literature are synthetized in Table 1.

The selected literature was collected in excel sheets comprising information about IPCC sub-regions (IPCC, 2021), climate scenarios, reference period, time period, corresponding GWL from pre-industrial (1850–1900), type of hazard, climate model and type of simulations, impact models (if available), sectors affected, risk metric, risk consequences, and additional comments and notes where it applies (Bednar-Friedl et al., 2022a). To assess the level of risk per warming level, we prepared synthesis notes per each line in the excel sheet and per each key risks. We grouped the notes per level of warming. Each author assessed separately the synthesis notes and assigned to a given risk level based on the key risk characteristics, such as magnitude, persistence, timing, irreversibility, and limited adaptive capacity. The author convened to build consensus using expert judgment approaches. The exercise was repeated multiple times until the spread of opinion per each warming level and corresponding risk level was minimized. The adaptation pathways are designed starting from the feasibility and effectiveness assessment whose details are given in the supplementary material of AR6 Europe Chapter (Bednar-Friedl et al., 2022b). A score was given to the effectiveness of each adaptation option based on qualitative and quantitative information in the literature on the corresponding risk reduction potential of the option. To build the pathways, options have been arranged on the pathways diagram based on information on either the timing or the risks reduction potential at a given warming level. Path dependencies, tipping points, the complementarity of options, and bundle of options were iteratively assessed by the author's team until consensus was reached on the final pathway design for a given risk. An overview of the stages of the assessments is provided in Figure 1. The pathways specific to the Europe key risks are illustrated in figure 13.29–13.32 of the Europe Chapter.

BOX 1 Methodology to derive key risks and adaptation pathways

We briefly describe the process in the chapter Europe to derive the key risks and design the adaptation pathways. The list of references assessed can be found in Bednar-Friedl et al., 2022b. A more elaborated description of the methodology can be found in the AR6 Chapter 16 “Key Risk across Sectors and Regions” (O'Neill et al., 2022). The key risks were identified considering the following:

- IPCC AR5 Europe, published in 2014 (which set the scene and where we came from) (Kovats et al., 2014).
- IPCC AR6 WGI, Chapters 11 and 12 (which assess climate extremes and regional hazards; Ranasinghe et al., 2021; Seneviratne et al., 2021).
- Sectorial sections in the Europe Chapter (namely Section 13.2–13.9).
- Detection and attribution assessment for Europe in the Europe Chapter (13.10.1) (Bednar-Friedl et al., 2022a; O'Neill et al., 2022).

TABLE 1 The table summarizes key findings from the key risks and adaptation effectiveness assessment performed in the context of the IPCC WG2 Europe chapter (Bednar-Friedl et al., 2022a).

	Description of the risk	Adaptation options	Characteristics of adaptation options and pathways	Synergies and trade-offs between KRs
KR1—Humans	Heat stress mortality and morbidity from heat extremes	• Behavioral changes such as applying sun cream or wearing light-colored clothes • Urban planning such as cool pavements, vegetation • Urban planning such as reducing building density • Building interventions, such as air conditioning or green or cool roofs • Heat health action plans • Heat early warnings	• Regional differences based on average temperature and past experience with heat stress. • Strong interaction with socioeconomic aspects • Long lead time for some transformative measures needed to contain risk at medium to high warming. • In some regions a combination of many (if not all) measures needed as limits are approached at increasing warming.	• Synergies with ecosystems protection and air quality • Air conditioning highly effective, but relying on excessive use of energy, strengthening urban heat island • Space limitation for nature-based solutions in urban areas and priorities given to other uses of available space (e.g., vehicle infrastructure) • Reduced effectiveness of nature-based solutions at increasing warming.
KR1—Ecosystems	Marine and terrestrial ecosystem disruptions from heat extremes and changes in average temperature	• Autonomous ecological adaptation such as acclimation, trans-generational plasticity, and evolutionary adaptation • Socio-Institutional Adaptation • Monitoring and warning systems • Conservation, e.g., protected areas • Climate adaptive management of protected areas • Increased habitat connectivity • Habitat restoration • Assisted migration • Assisted evolution	• Lack of monitoring hinders assessment of adaptation effectiveness and hence pathway construction • Planned adaptation is fundamental to support autonomous ecological adaptation	• Climate-change impacts on ecosystems will continue to be exacerbated by interactions with non-climate driver such as habitat fragmentation or loss, pollution, or resource overexploitation, • Human mitigation actions can negatively impact ecosystem integrity • Adaptation and mitigation actions via nature-based solutions can generate space and protection for ecosystems
KR2—Crop production	Losses in crop production from compound heat and dry conditions and weather extremes affecting food supply and prices	• Irrigation • Sowing/harvest dates change • Change of cultivars • Land cover change • Plants breeding (including GMO) • Soil management • Mixed use such as agroecology and agroforestry • Agricultural policies change • Training and information	• With increasing warming multiple, if not all, adaptation options needed but that may not reduce all risk in all places.	• Potential for lock in with irrigation • Potential for lock in consumer behavior (e.g., shifting to plant-based diets) and technological innovation (alternatively sourced proteins)

(Continues)

TABLE 1 (Continued)

	Description of the risk	Adaptation options	Characteristics of adaptation options and pathways	Synergies and trade-offs between KRs
KR3- Water scarcity	Reduced availability of water resources	• Storage in reservoirs, dams, and water towers (supply side) • Diversion via canals and pipelines (supply side) • Desalination (supply side) • Water reuse (supply side) • Water saving and efficiency (demand side) • Economic instruments like water pricing (demand side) • Land management (demand side) • Drought monitoring and early warning	• With increasing warming multiple, if not all, adaptation options are needed that may not reduce all risk in all places. Transformative adaptation will then be needed.	• Potential for cascading impacts beyond water sector, i.e., on agriculture, energy, industry • Potential for maladaptation with ecosystems (e.g., water extraction and diversion)
KR4 – Floods (riverine, pluvial, coastal)	Flood risks for people, infrastructure, and cultural heritage	• Early warning (protection and accommodation) • Flood defenses (structural protection) • Accommodation by retention and diversion • Managed retreat • Avoidance (no-build zones) • Supporting measures such as flood insurance • Protection through Ecosystem-based adaptation (e.g., river and wetland restoration) • Protection through sediment-based (e.g., beach nourishment) • Wet and dry proofing of buildings (accommodate) • Retention measures such as green spaces in cities • Improve drainage in cities (accommodate)	• Distributed across drivers of flooding, e.g., river, pluvial, sea-level rise that potentially compound. • Dichotomous futures between protect and accommodate-relocate.	• Potential for maladaptation and adverse impacts to ecosystems

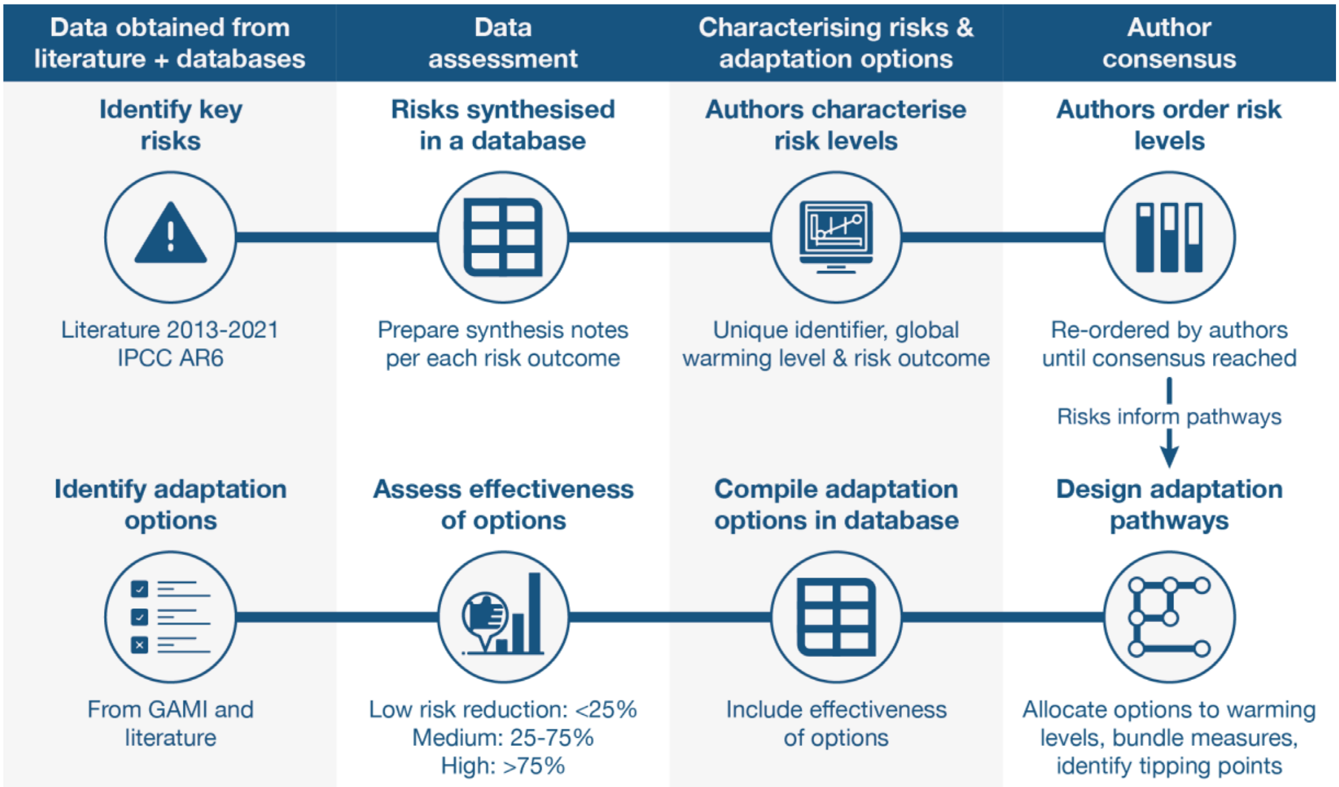

FIGURE 1 Workflow explaining the stages to derive the burning embers diagram (top) and to design the adaptation pathways (bottom). As studies in the literature are not evenly distributed across geography and time, the confidence in the assessment will vary especially in response to high warming and uncertainty in the literature.

3 | WHAT A COMBINATION OF KEY RISKS AND ADAPTATION PATHWAYS CAN SHOW

Adaptations to the four key risks pose significant challenges for decision makers. The key risks and adaptation assessments for Europe have helped highlight the challenges of both adaptation and risks, as illustrated in Table 1. In the following, we develop arguments on how these challenges can be tackled using warming-sensitive adaptation pathways. This approach offers a framework for decision making at different geographic scales, and a starting point for context-specific and more in-depth risk analyses.

3.1 | Challenge 1: Dynamic adaptation planning embedded in specific contexts

Particularly in highly exposed and vulnerable regions, a dynamic adaptation approach to heat extremes (KR1) would consist of first combining existing measures (e.g., behavioral adaptation) to reduce risks as fast as possible. This will allow time to introduce other more resource-demanding measures for transfromative adaptation with longer lead times, for example, heat proof land development (e.g., reduce building density, enhance green infrastructures, and redesign urban spaces). However, given that impacts in heat exposed regions are unfolding at an accelerated speed and intensity (Raymond, Matthews, & Horton, 2020), current adaptation is not sufficient to keep up with this rate of change. Adaptation is currently focused mainly on "low hanging fruit", existing options, and near-term risks. As a result, adaptation shows a considerable level of inertia, making societies ill-prepared to withstand plausible but, as yet unexperienced heat extremes (Huggel et al., 2022). These actions may reinforce existing ways of living, ultimately making the necessary transformative adaptation harder. For example, the use of air conditioning or air-cooling devices will in the medium to long term reinforce existing energy inequalities, create dependence on scarce resources (e.g., water and energy), and does not build long-term resilience (Andrijevic et al., 2021; Davis et al., 2021). Such measures will just delay action and lock in societies. The suggested pathway approach highlights that such adaptation options only have a limited effect or limited time span (Magnan et al., 2020). However, it is important to keep in mind that adaptation may reach its limits in highly exposed and vulnerable locations soon and at lower GWLs (Bednar-Friedl et al., 2022a). Conversely, in less exposed regions more time would be available to implement a portfolio of measures. For example, behavioral adaptation in Northern Europe has significant adaptation potential over the next years, emphasizing the need to tailor pathways to regional and local conditions (Bednar-Friedl et al., 2022a).

The importance of the regional context is also evident for adaptation to cross-sectoral water scarcity (KR3). In Southern Europe, many adaptation options, such as irrigation and water reservoirs and water transfer, are already implemented today, but their future availability and potential extension depend on available precipitation (Bednar-Friedl et al., 2022a; Greve et al., 2018). For medium warming, additional investments in water infrastructure and alternative technologies (including water recycling and reuse, and desalination) will be needed, and these supply side measures are particularly effective when combined with demand side measures such as improvements in water efficiency and behavioral changes (Greve et al., 2018; Papadaskalopoulou et al., 2015). At high GWL, these measures may not be able to avoid water shortages during drought periods, necessitating water rationing, that risks abandonment of farmland or the development of alternative livelihoods (Papadaskalopoulou et al., 2015; Teotónio et al., 2020). In Western and Central Europe, current risk levels are lower but there is a need for investments in large water infrastructure and alternative technologies (including storage) to reduce future risks at higher warming levels (Greve et al., 2018). Yet, socio-cultural acceptability, for example, of water reuse, might pose a challenge (Papadaskalopoulou et al., 2015). These examples showcase different plausible adaptation pathways, which can be further evaluated and selected based on local-specific realities. They can also show that a step-change is needed in adaptation (transformative) and/or that limits may be reached with available measures unless global warming is mitigated. Given the speed of change, there is a pressing need to combine most and, if possible, all available measures in certain locations (Figure 2).

3.2 | Challenge 2: Compound hazards and risks require consideration of interaction and interdependencies of adaptation

The last decade has shown how hazards are compounding and co-occurring to give rise to more widespread and complex risks (Bevacqua et al., 2021; Zscheischler, Martius, Westra, Bevacqua, Raymond, Horton, et al., 2020). Key examples are compound heat and drought hazards (summer 2018, 2022), concurrent heatwaves (days and night heat extremes summer 2015, 2019, 2022), hazards affecting several regions at the same time (summer 2021 flood in central Europe and heat extremes in southern European regions), and dry extremes (fire, droughts, heat). Western Central and Southern regions will be increasingly affected by compound heat and dry conditions (Sutanto et al., 2020) with impacts on agriculture, and crop production in particular, already evident today. Crop losses have been recognized as a key risk in both regions in response to future warming (Bednar-Friedl et al., 2022a). Adaptation options for crops have focused on reducing heat stress or giving relief from droughts by both reducing canopy temperature and drought impacts via irrigation (Webber et al., 2018). Crop breeding for drought and heat tolerance using modern phenotyping approaches are important to generate resistance to both heat and dry conditions (Costa et al., 2019). The focus of research on heat and drought has been on cereals, thereby creating important gaps in understanding for vegetables or fruits (Bednar-Friedl et al., 2022a).

Interacting heat and drought extremes demand a sequencing and portfolio of measures to address their impacts on crops (Figure 3). For example, irrigation is an effective approach to reduce temperature around the crop and reduce impacts of drought (Donatelli et al., 2015), but increases demand for already limited water resources. Changes to land use, such as agroecology, agroforestry, and breeding have long lead time. Planning ahead will avoid future lock-ins, such as relying on irrigation in regions that will be confronted with increasing heat and dry extremes (Webber et al., 2018).

Hazards and risks compound and cascade leading to concentrated areas of multiple significant risks, particularly in Southern European regions, coastal zones, and urban areas (Bednar-Friedl et al., 2022a). Agricultural areas might be affected by compound heat and dry events (KR2) while at the same time experiencing water scarcity (KR3), for example, in some key agricultural areas of Central Europe (Byers et al., 2018). Water management for food production is becoming complex due to the need to satisfy other social and environmental water demands. Adaptation focusing on single risk such as crop yield losses due to extreme temperatures ignores the compound and cascading effects of multiple risks (Simpson, Mach, Constable, Hess, Hogarth, Howden, Lawrence, Lempert, Muccione, & Mackey, 2021). Spillover effects of adaptation responses across sectors may not reduce risks overall and potentially lead to maladaptation.

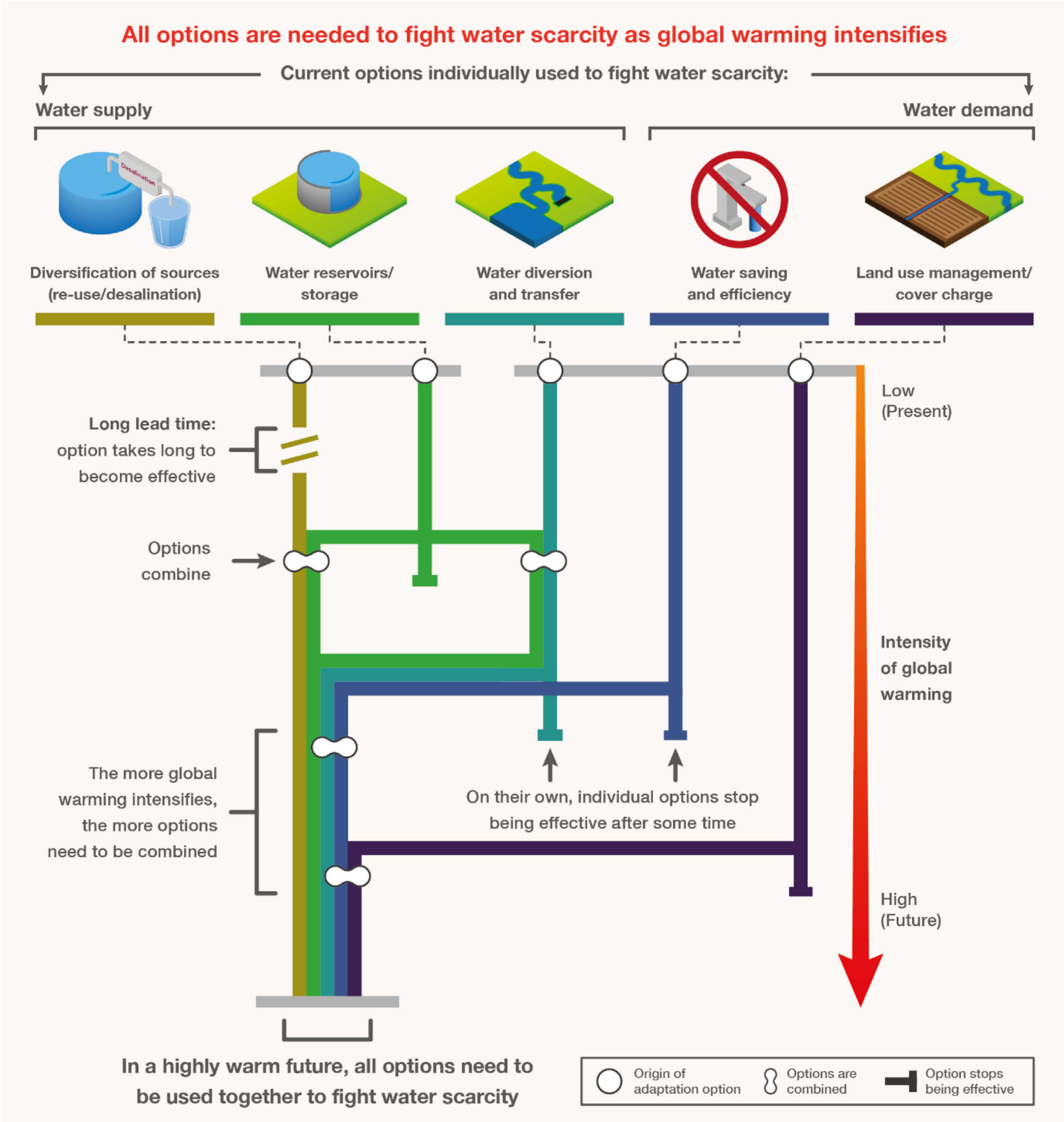

FIGURE 2 This figure illustrates the pathways to fight water scarcity. Risk intensifies as warming progresses. The timing when all measures must be combined to increase effectiveness varies depending on the local context. From top to bottom, the figure shows a portfolio of measures derived from the effectiveness assessment. The different colors correspond to each option at its start indicated by the white circles. The connected smaller circles indicate combinations of two or more options. Notes clarify how to read the diagram. Uncertainty of effectiveness of measures is often higher under higher degrees of warming and further into the future as large-scale societal transformation is more difficult to anticipate. The same structure applies to Figures 3–5.

Climate change mitigation actions, for example, reforestation, will also compete for land and water with agriculture (Parmesan et al., 2022). This tension can be uncovered by exploring the pathways for each risk and carefully considering risk interactions, as well as interactions with mitigation actions, and their combined outcomes (Schlumberger et al., 2022). For example, agricultural risk pathways show that water irrigation, in combination with water demand

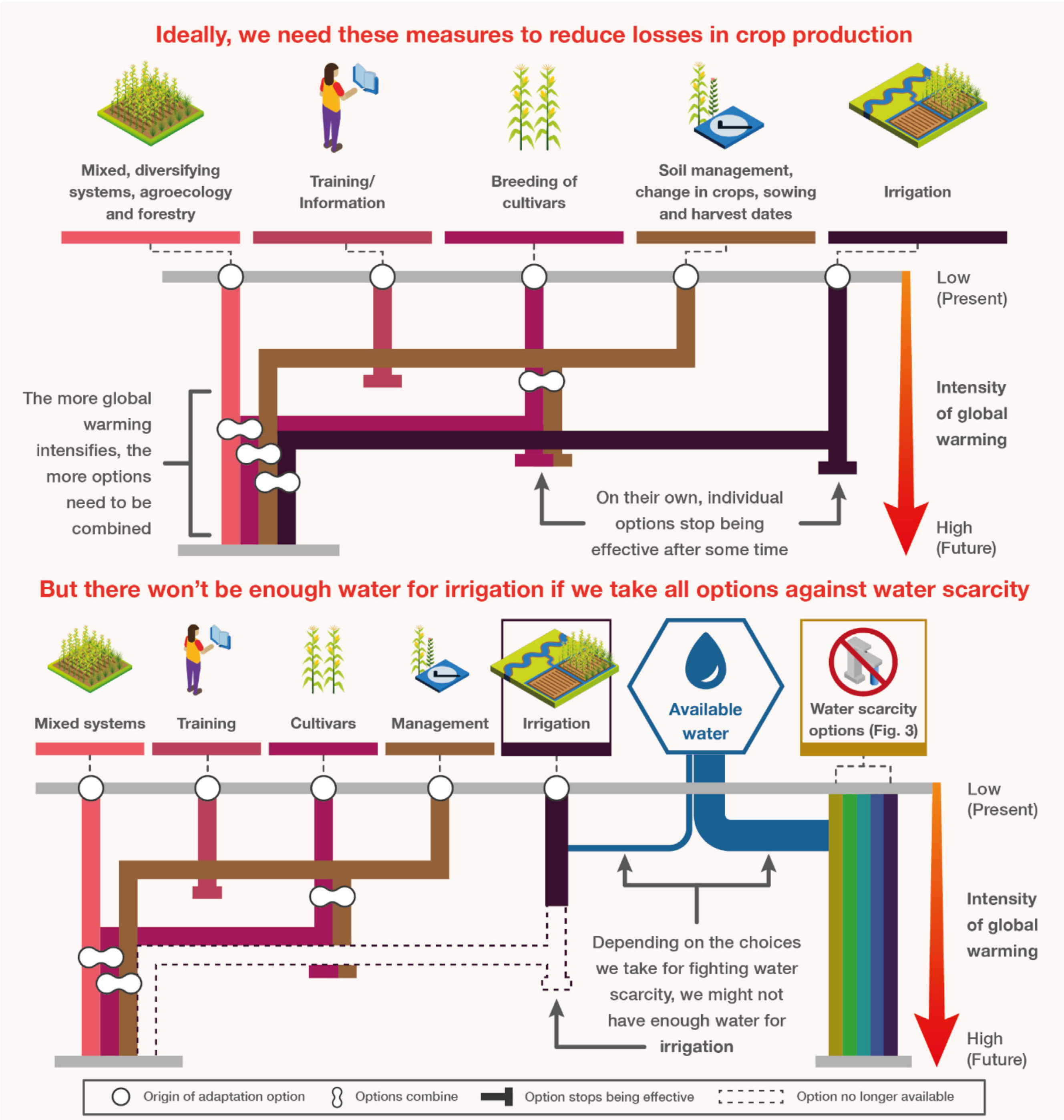

FIGURE 3 The top panel represents the illustrative pathways to reduce losses in crop production. The success of adaptation depends on limited resources such as water which is increasingly being constrained as warming intensifies (bottom panel). This also means that without measures aiming at reducing water demand, there would not be enough water for irrigation.

reductions, can reduce risks in certain locations (Webber et al., 2018). However, for high warming, this adaptive capacity is considerably reduced (Gerveni et al., 2020) and leads to maladaptation and lack of development of alternative adaptation options. Where the ability to irrigate is limited by water availability and other adaptation options are insufficient to mitigate crop losses, agricultural land abandonment becomes be the only option left (van Ginkel et al., 2020). New pathways are needed to account for risks interconnection (Figure 3, bottom panel). Increasing protected areas for ecosystems (KR1) will limit land for crop production, fisheries, and climate mitigation actions. Planning and balancing need to happen urgently by considering both human and ecosystem sustainability (Henry et al., 2022). Bioenergy generation with carbon capture and storage (BECCS) will draw on similar resources as agriculture, threatening to limit the duration of some adaptation effectiveness due to higher demand, potentially with wider negative impacts on food and water security (IPCC, 2022b). Combining multiple adaptation pathways for these three key risks (KR1, KR2, and KR3) and considering the needs for mitigation approaches will show tensions between and losses of adaptation actions and facilitate robust decision making for these future risks.

3.3 | Challenge 3: The need to consider the long-term in short-term decisions and the emergence of a dichotomy

Adaptation pathways have been widely used in the context of flood and sea level rise (Haasnoot et al., 2019; Magnan & Duvat, 2020). Coastal adaptation to flood risks (KR4) requires consideration of both short-term and long-term needs, as sea-level rise will continue for centuries (IPCC, 2021). Additionally, akin to water supply infrastructure, adaptation options, such as engineered coastal protection, need long-term planning and implementation, and have a long-term legacy (Oppenheimer et al., 2022). Across Europe, a strong reliance on protection attracts people and the placement of assets in low lying coastal areas (Haasnoot et al., 2021). By developing warming-sensitive pathways, the near and long-term solution space, as well as potential limits and path-dependencies of adaptation options can be highlighted. These pathways can guide practitioners to better understand the scale of the problem, potential lock ins, associated uncertainties, and long-term need for adaptation. What they often do not consider are the relative costs and trade-offs resulting from implementing values or costs and values for local communities (Dietz et al., 2005; Kenter & O'Connor, 2022) or the non-monetary values of coastal social-ecological systems (Cooley et al., 2022). Consequently, decision making raises questions of legitimacy given the plurality of perspectives for collective problem solving (Steele, 2001) which are important to successful adaptation (Schmidt et al., 2022).

If long-term perspectives are integrated into adaptation decision making, moving from incremental measures (e.g., protection measures to reduce the hazards) to accommodation (reducing vulnerability) and to managed retreat or avoidance measures (reducing or avoiding exposure) becomes evident (Oppenheimer et al., 2022). Coastal flood risks adaptation pathways can combine these generic adaptation categories (i.e., protect, accommodate, and retreat/avoid) in two ways: on one hand, pathways combining accommodation and protection measures such as retention, diversion, and flood defense; and, on the other hand, pathways anticipating accommodation and managed retreat, while allowing for protection and accommodation for some time. Due to specific environmental and human constraints and opportunities in particular locations, not all adaptation measures may be considered or appropriate everywhere. For example, large-scale relocation is not preferred in most cities, and accommodation of buildings can be considered only in sheltered areas.

Both inland and coastal flooding adaptation pathways show that there are limits to ecosystem-based and engineering protection under medium to high GWLs (i.e., global temperature increase exceeding 3°C) due to lack of space and time or due reduced sediment availability and high temperatures for ecosystem-based measures. While developing adaptation plans in flood prone areas, decision makers can realize which adaptation pathways becomes more difficult once a specific adaptation measure has been implemented. For example, in Figure 4, implementing protection in the short term has a long-term societal legacy. The figure also highlights the long-term dichotomy between two pathways, for example, one that combines flood defenses with wetlands and the other that combines planned relocation with wetlands.

3.4 | Challenge 4: Pathways support planning even with limited knowledge of effectiveness

For some systems, such as human health or water, regular reporting on the outcomes of adaptation and the evolution of climate change risks is facilitating the ongoing assessment of adaptation progress. For others, such as natural systems (KR1), the lack of systematic long-term monitoring results in knowledge gaps on effective adaptation options (Hoppit et al., 2022). Ecosystems on land and in the ocean are already responding to climate change via autonomous adaptation, phenotypic plasticity, changing timing of seasonal events, and evolutionary adaptation (Bednar-Friedl et al., 2022b). However, with increasing warming more species will reach their thermal tolerance limits. For natural systems, the

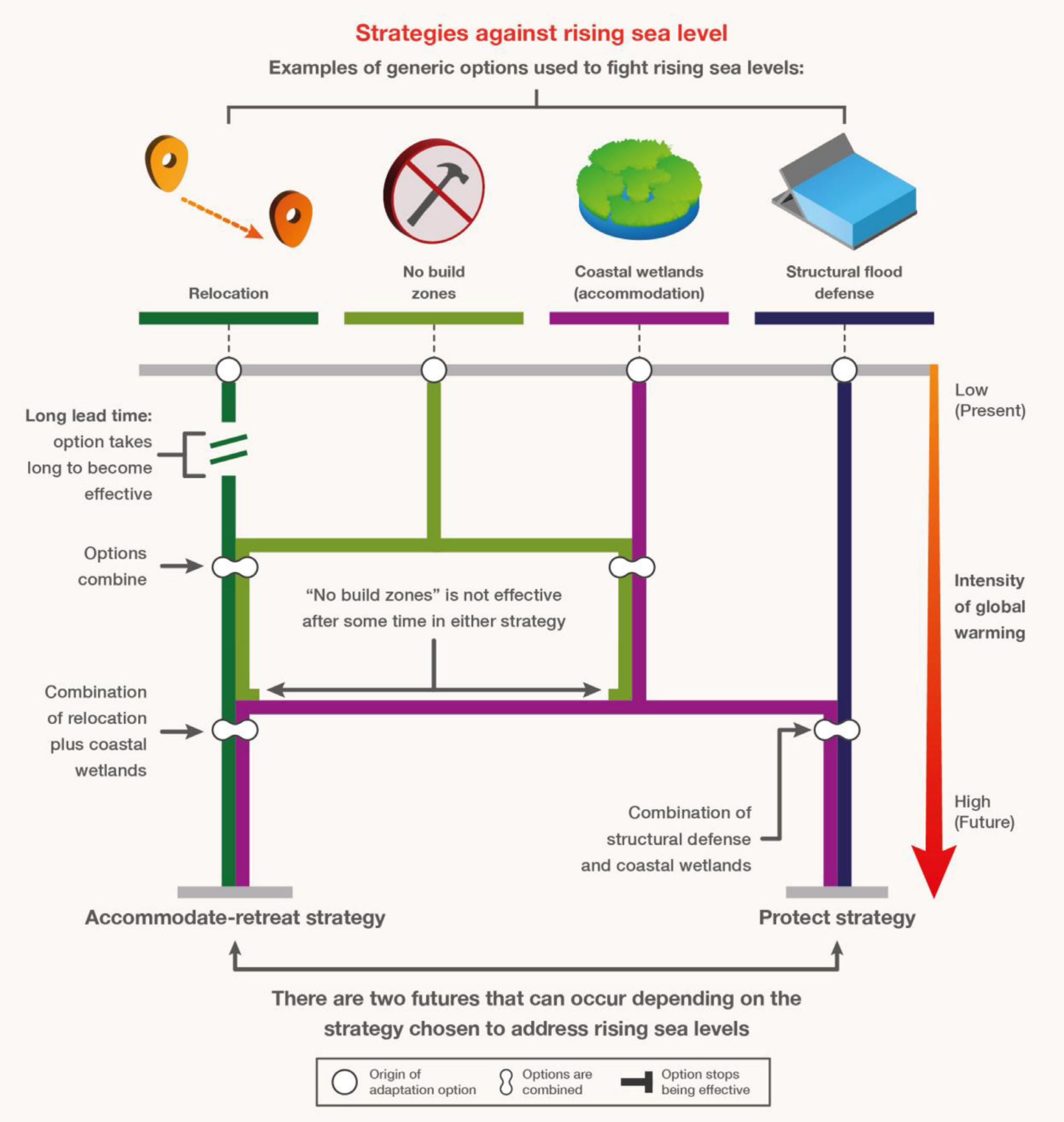

FIGURE 4 Illustrative adaptation pathways showing examples of options to adapt to rising sea levels and the emergency of a dichotomy between two different futures. Long-term planning is key to avoid lock ins in case of risks from sea level rise and coastal flooding. The timing of specific options can vary in specific contexts, for example, the decision to not build a hard defense in the short or medium term and only shift to hard infrastructure in the longer term would be an intermediate between accommodate and protected.

impacts of human pressures such as pollution and habitat distribution complicate the assessment of adaptation effectiveness.

Most managed adaptation approaches focus on reducing vulnerability of ecosystems, through the relative risk reduction of protected areas (Lubchenco & Grorud-Colvert, 2015). Additionally, a lack of connection between land use change, climate impacts on rivers, and the coastal ecosystems hinders a joint up risk assessment for these important ecosystems (Schmidt et al., 2022). Habitat diversification in protected areas is considered beneficial, but the knowledge of losses of protected species and habitat and the resulting integrity of the network is limited (Grorud-Colvert et al., 2022).

Despite these knowledge gaps, adaptation pathways serve as tool for sequencing multiple options enabling a departure from solely focusing on a single adaptation option. Some measures are readily available and could be implemented, such as the increase of the area and diversity of the habitats in protected areas (Grorud-Colvert et al., 2022; Figure 5). Since limits of ecological adaptation options are known (Bednar-Friedl et al., 2022a), pathways that increase resilience and reduce climatic and non-climatic pressures, such as identification of microrefugia (Brooker et al., 2018), reduction

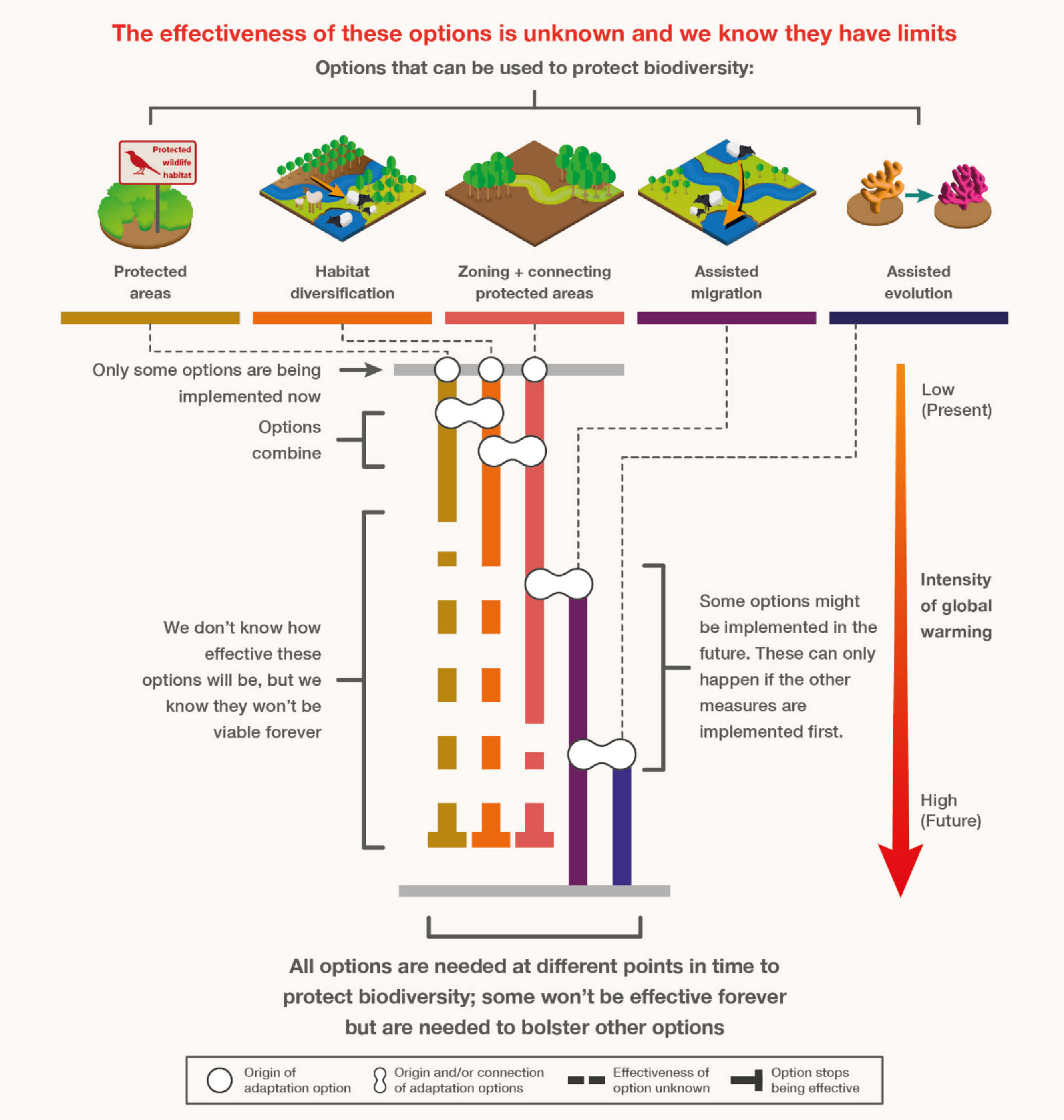

FIGURE 5 Illustrative adaptation pathways to reduce ecosystem disruptions. Compared with Figures 2–4, there is considerably more uncertainties in the effectiveness of adaptation options as it is illustrated by the dashed pathways. However, it is known that these options have limits.

of pollution and habitat destruction, and approaches which allow determining effectiveness, such as monitoring, will strengthen adaptation implementation (Cooley et al., 2022; Parmesan et al., 2022). Additionally, joint planning with mitigation approaches and food production, which compete for land and water with natural ecosystems, allowing the best geographic placement of these measures (Griscom et al., 2017).

4 | CONCLUSIONS

How to respond effectively to more complex climate risks while juggling complex adaptation trade-offs and synergies will be a key challenge for researchers and adaptation practitioners in the coming decades (Simpson, Mach, Constable, Hess, Hogarth, Howden, Lawrence, Lempert, Muccione, Mackey, New, et al., 2021). Timing of actions is of paramount importance. Delayed action not only increases the adaptation gap, but also compromises the portfolio of actions and increases the residual risks (Magnan et al., 2021). Adaptation planning for compound and cascading risks is essential and will become more so in the near future, as our world warms to 1.5°C GWL and beyond (IPCC, 2022a). Appraising the effectiveness of available adaptation options to limit future risk is fundamental to comprehensively inform adaptation policy and decision making (Tamura et al., 2019). Adaptation pathways offer a snapshot of plausible futures and are illustrative for a given risk considering the breadth of climate and human interactions (Haasnoot et al., 2020). There is the potential for catastrophic events, shocks, and unanticipated events that are not represented in current scenarios and risk management, (Kemp et al., 2022). An agile and flexible risk management approach would not completely avoid such residual risks but has still major advances over more rigid risk management planning (Kemp et al., 2022; Magnan et al., 2020).

In essence, adaptation pathways provide invaluable insights into the scale of interventions needed for adapting to future risks under climate change, while highlighting the intricate challenges of navigating diverse norms, values, and responses to these risks (Haasnoot et al., 2020). The development of inclusive pathways hinges on effectively capturing diverse perspectives and values through meaningful deliberation. Importantly, adaptation decisions create long-lasting legacies, with pathways able to represent divergent futures, as illustrated in Figure 3, underscoring the importance of exploration of such alternatives. When planning for multiple long-term risks, trade-offs within adaptation pathways become pronounced. The diminishing choices with increasing warming define critical timelines, while the timing of combining adaptation measures varies considerably by region and context (see Figure 2). However, in many contexts around the world, the so-called solution space to adaptation planning and pathway approaches is limited, often due to pre-existing rules and practices, scarce knowledge and resources, and limited political will (Abel et al., 2016; Haasnoot et al., 2020). Expanding the solution space requires accelerating the adoption of legislation, instruments, and mechanisms that allow for forward-looking adaptation planning. This also requires continuous monitoring and evaluation of progress, not only to understand the rate of climate change but whether the rate of policy implementation is adequate and effective or if more or different actions are needed. This is particularly true for those risks where we currently know little about the effectiveness of future adaptation options (Figure 5). These decisions need to be based on integrated deliberative valuation of community and policy response options within the context of shared values and broad sociocultural discussions of the impacts of different visions of our futures.

While this perspective builds on the knowledge and learning developed in the context of Europe-focused literature, the outcomes are not unique to the European region and can be transposed to other regions or sectors. In many places across the world, particularly the most vulnerable regions, the challenge decision makers face is often more severe (Birkmann et al., 2022). Knowledge about climate impacts and future risks are less comprehensively available, evidence on adaptation actions are less well documented, and socioeconomic conditions create lower adaptive capacity (Berrang-Ford et al., 2021). Nevertheless, the approach highlighted in this article could lead to comprehensive assessments of risks and adaptation and avoid making ill-informed decisions which will eventually result in lock ins and maladaptation.

Furthermore, it is worth mentioning that here we explored plausible futures in line with the latest IPCC reports (IPCC, 2023). However, there is also literature discussing the limitations of scenarios (van Beek et al., 2022) and advocating to complement scenarios with imaginary futures (Robinson et al., 2011; van der Voorn et al., 2023). Approaches such as back-casting complemented with dynamic adaptive policy pathways could then be used to further explore pathways.

If we are to adapt to a 1.5°C warmer climate in the next couple of decades, it must be done continuously and dynamically. Illustrative pathways allow the design of a world where climate change adaptation takes place as the options for adaptation become increasingly more complex and constrained.

AUTHOR CONTRIBUTIONS

Veruska Muccione: Conceptualization (lead); formal analysis (lead); funding acquisition (lead); methodology (equal); project administration (lead); writing – original draft (lead). **Marjolijn Haasnoot:** Conceptualization (lead); methodology (equal); writing – original draft (equal). **Peter Alexander:** Conceptualization (equal); methodology (equal); writing – original draft (supporting). **Birgit Bednar-Friedl:** Methodology (equal); writing – original draft (supporting). **Robbert Biesbroek:** Conceptualization (equal); methodology (equal); writing – original draft (equal). **Elena Georgopoulou:** Writing – original draft (equal); writing – review and editing (equal). **Gonéri Le Cozannet:** Conceptualization (equal); writing – review and editing (equal). **Daniela Schmidt:** Conceptualization (lead); methodology (lead); writing – original draft (lead); writing – review and editing (equal).

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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