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Supporting climate resilient development planning – a dynamic adaptive pathways based approach and an illustrative case from Cork City, Ireland

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ABSTRACT

To achieve climate resilient societies, climate adaptation, mitigation, and sustainable development (AMD) are all necessary. The concept of "climate resilient development pathways" (CRDP) recognizes this as intertwined challenges. However, no systematic approach exists for the creation and appraisal of CRDP that integrates adaptation, mitigation, and sustainable development over time, and addresses the interactions between these policy objectives. Building upon Dynamic Adaptive Pathways Planning (DAPP), this paper presents a decision analysis approach for integrating CRDP policy objectives in Climate Resilient Adaptive Pathways Planning, or CRDAPP. Key additions in this approach are: a) using visioning to design CRD strategies for managing pathways complexity; b) introducing target points for sustainable development and climate mitigation action setting, to help sequence measures into alternative pathways, alongside traditional performance thresholds; and c) defining types of adaptation, mitigation and development interactions to systematically evaluate actions and pathways. We test the approach in an illustrative case study in Cork City, Ireland. The CRDAPP steps are carried out for the city, with multiple pathways designed and critical decisions over time identified. The resulting CRDAPP analysis provides insights into the range of options for Cork on how to combine mitigation, adaptation, and sustainable development actions over time, to work toward different future states of the city. CRDAPP can support decisionmakers to better align adaptation, mitigation, and sustainable development action into their planning processes.

1. Introduction

The impacts of climate change and the growing world population are mounting pressure on Earth's limited resources and the lives and livelihoods of people, propagating the unequal distribution of wealth and development. Sustainable development and climate action, including both mitigation and adaptation, are slow and largely siloed (Berrang-Ford et al., 2021; Howarth and Robinson, 2024; UNEP, 2023). Historically, local, national, and international policies have largely singled out adaptation, mitigation, and sustainable development (AMD), with mitigation outpacing adaptation policies and action (Sebestyén et al., 2023). It has become increasingly clear that these three policy objectives are strongly interconnected and siloed approaches are not cost effective, do not reflect the multidimensionality and complexity, and could even lead to mal-adaptation and –mitigation, or other unintended consequences (Howarth and Robinson, 2024; IPCC, 2022). Concrete examples illustrate the interplay between AMD. For instance, urbanization and the need for constructing houses could result in more GHG emissions, and urban greening for adaptation can lead to gentrification, counteracting sustainable and just development goals (Chapple et al., 2022). Nevertheless, urban greening and house insulation to adapt to higher temperatures can reduce heat stress and thus reduce the need for cooling through energy consuming air-conditioning during summer or the need for heating during winter. There is an increasing need to tackle adaptation, mitigation, and sustainable development together to effectively deal with on-going and future climate change and socio-economic challenges in a way that moves towards resilient and thriving futures for all (Schipper et al., 2022).

The IPCC 6th Assessment Report emphasized a key concept for implementing greenhouse gas mitigation and adaptation measures to support sustainable development for all, so-called "climate resilient development" (CRD). The associated development trajectories that

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successfully integrate these three policy objectives are "climate resilient development pathways" (CRDP) (Schipper et al., 2022). CRDP needs to account for the complex interactions between adaptation, mitigation and sustainable development over time and under uncertainty, as well as for justice – including procedural justice (fairness of processes), distributive justice (fairness of outcomes), and interactional justice (fairness in interpersonal treatment) (Reckien et al., 2025; Schlosberg and Collins, 2014).

CRDP requires broad and structural societal changes, with extensive implications for governance, institutions, and economic, social, ecological and political systems change. New approaches are needed to support the realization of CRDP's promises (Schipper et al., 2022). However, alongside this, CRDP also involves technical systems like utilities, spatial planning, and transportation, which have received less attention in the CRDP discourse. Supporting these kinds of decisions with better integration and systematic policy alignment is also an important part of the transition toward CRDP. This requires the concept of CRDP to become more operational for decision making processes and the complexity to become manageable in planning AMD measures over time. While CRDP may catalyse transformational change, it will unfold through gradual transitions rather than all at once requiring the technical and social sciences to evolve together (Geels and Schot, 2007; Patterson et al., 2017, 2021).

There are existing methods and approaches that deal with one or two CRD(P) policy objective(s). For example, adaptation pathways (e.g. Dynamic Adaptive Pathways Planning (DAPP)) (Haasnoot et al., 2019, 2013), development pathways which combine adaptation and development (Butler et al., 2022; Gajjar et al., 2019), or the STEPS approach focusing on sustainability (Leach et al., 2007), among others. Initial work on CRDP has included qualitative and descriptive cases, and limited conceptual and empirical work (Kareem et al., 2020; Singh and Chudasama, 2021; Taylor et al., 2023; Werners et al., 2018). Approaches developed within the Decision Making Under Deep Uncertainty (DMDU) community effectively deal with uncertainties and can break down complex planning processes that could help operationalize CRDP (Haasnoot et al., 2019, 2013; Marchau et al., 2019). For instance, Robust Decision Making (Lempert, 2019) can help to identify robust decisions and contingency actions to deal with uncertainties. Scenario discovery (Bryant and Lempert, 2010) could help to identify relevant scenarios for AMD. Climate Risk Informed Decision Analysis (CRIDA) demonstrates how methods like Decision Scaling and DAPP can be combined to assess risk and develop adaptive plans under deep uncertainty (Mendoza et al., 2018). Adaptive Governance (Brunner and Lynch, 2017; Chaffin et al., 2014) could support with institutional arrangements and roles of different stakeholders in adaptive pathways planning for CRD. Nevertheless, there is no general procedure for developing and evaluating CRDP, that integrates AMD objectives and includes the time dimension of planning (Werners et al., 2021). Schipper et al. (2022) highlighted the need to design pathways for the practical pursuit of CRD in the short, medium and long-term, including understanding the efficacy of different adaptation, mitigation and sustainable development interventions in reducing climate risk and/or enhancing opportunities for CRD. In order to accelerate climate action, it is critical to further operationalize CRDP to support policy and planning.

The expertise of many fields is needed to inform and support the development and implementation of CRDP. There will not be one way or one framework that fully operationalizes this concept, but many contributions to a comprehensive approach. In this paper, we take decision analysis as one starting point to explore how it can help understand and evaluate interactions between adaptation, mitigation and sustainable development actions over time. In doing so, we aim to share a first attempt at integrating adaptation, mitigation and sustainable development in a decision analysis and of the creation of an adaptive CRD pathways plan. As an analytical framework for assessing options over time and creating dynamic adaptive pathways plans, DAPP offers a suitable starting point (Haasnoot et al., 2019, 2013; Marchau et al., 2019). We elaborate the Dynamic Adaptive Pathways Planning approach (DAPP) for CRDP objectives. DAPP resonates with planners dealing with uncertainties, as demonstrated by its wide adoption in a variety of planning topics and contexts in the past decade (Haasnoot et al., 2024). Additionally, DAPP has been expanded to address emergent challenges and planning needs, like multi-risk, and has numerous supporting scientific papers and practical guidelines (Haasnoot et al., 2024; Lawrence et al., 2018; Lawrence and Bell, 2024; Schlumberger et al., 2022). While DAPP has been predominantly applied to adaptation, its ability to address mitigation and development issues, and its use in participatory analyses is recognized (Challinor et al., 2018). To move from DAPP to CRDP, particular attention is needed for (1) integrating AMD objectives into tangible pathways over time, (2) assessing the interactions between AMD measures, and (3) understanding the effectiveness and lifetime of mitigation and sustainable development actions.

Building on DAPP, this paper presents a stepwise approach for CRDP decision analysis, called: Climate Resilient Development Adaptive Pathways Planning (CRDAPP). CRDAPP is introduced in Section 2. A first exploratory and illustrative application of CRDAPP for the city of Cork, Ireland, is made in Section 3. The value, limits and opportunities for CRDAPP are then discussed in Section 4, and conclusions are drawn in Section 5.

2. CRDAPP for climate resilient development pathways (CRDP)

The Climate Resilient Development Adaptive Pathways Planning (CRDAPP) approach supports the design of CRDP through a structured decision analysis, addressing AMD interactions over time for the development of dynamic, adaptive pathways that can be used to navigate uncertainty. As in the original DAPP approach, CRDAPP aims to map alternative combinations and sequences of actions (pathways) over time and potential transfers between these pathways. These pathways are stress tested for their robustness under different future conditions using a range of scenarios. In this way, adaptive pathways differ from traditional planning that defines a single trajectory, or pathway. This is important for dealing with uncertainties, and more so for CRDP, due to the complex interactions between AMD measures and objectives. However, developing and integrating multiple pathways for different policy objectives quickly becomes complex, as many more measures are at play and the interactions between measures need to be captured. To address this for CRDP planning, we added new elements to the original DAPP approach. We use visioning as one way to deal with the complex AMD interactions and to identify integrated CRD strategies that serve as the basis for building multiple pathways towards different visions. In addition to traditional adaptation thresholds or tipping points, a new type of threshold is defined, a target point, to be able to include actions towards mitigation and sustainable development targets. In order to build and evaluate pathways, we identify three main types of AMD interactions between measures: feasibility; effectiveness; and side-effects.

Taking these new elements into account, the overall CRDAPP approach consists of seven main steps (Fig. 1). Each step is described in the following sections.

Step 1. Map the decision context.

Mapping the decision context aims to derive insights into the circumstances surrounding the decision-making processes and its consequences. The objectives, goals, targets and measures for AMD are identified through reviewing existing policy documents and stakeholder engagement, on the local as well as regional to (inter-)national levels. In addition, a wide range of relevant information is collected, from climate change and risk information (e.g. sea level rise, heat extremes), to (local) greenhouse gas inventories, socio-economic and demographic data, and vulnerability and distributional impact assessments, among others. Stakeholders, institutional complexity, political processes, and power dynamics are also analysed, together with their roles and interrelations (e.g. using methods by Barbrook-Johnson and Penn, 2021; Mitchell et al., 1997; Zingraff-Hamed et al., 2020). Meetings, workshops,

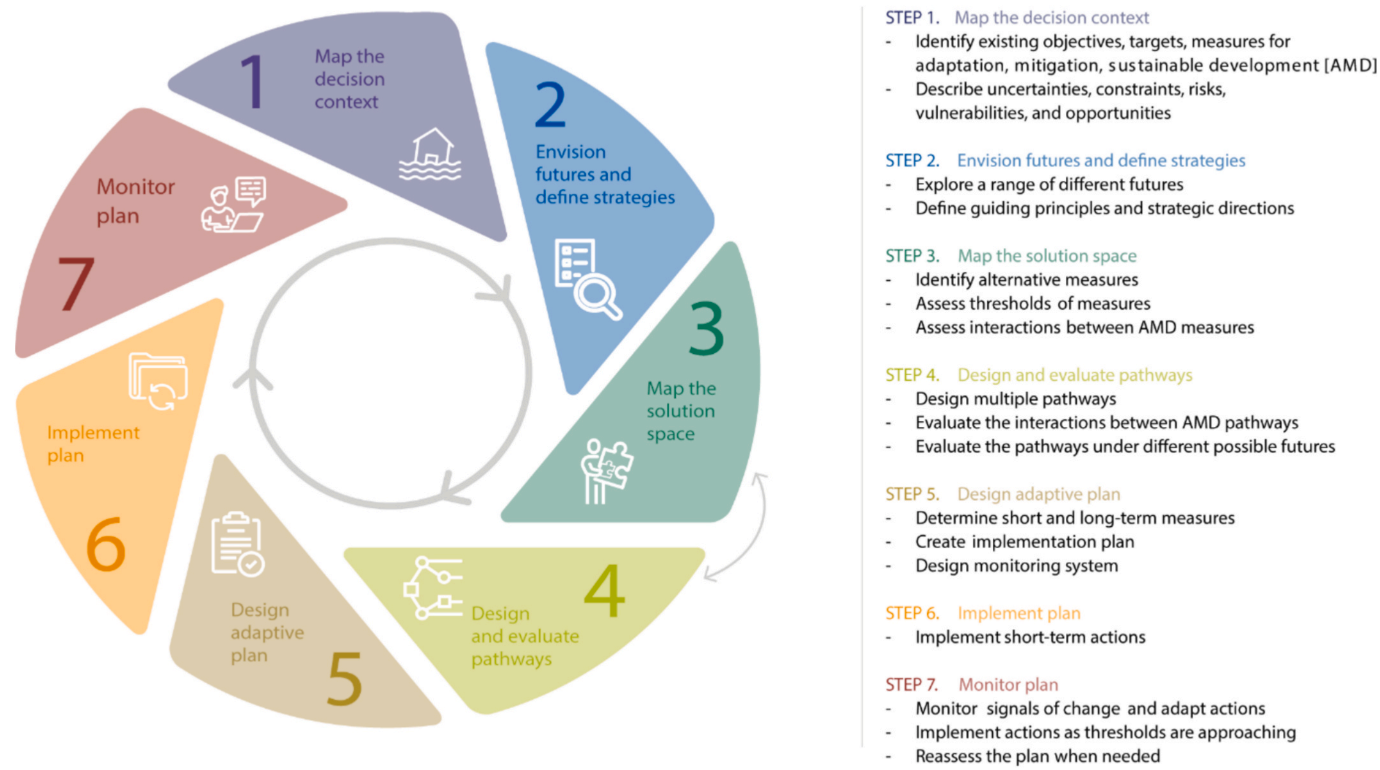

Fig. 1. Key CRDAPP steps for climate resilient development pathways (CRDP), building on DAPP (Haasnoot et al., 2019). Key novelties include visioning to design CRD strategies and pathways while dealing with complexity (step 2), target points are added next to performance thresholds for assessing adaptation, mitigation and sustainable development measures (step 3), and three types of adaptation, mitigation and sustainable development interactions are defined to build and evaluate pathways (step 3 and 4).

interviews and community outreach, can be used to establish a participatory planning process and to ensure a representative understanding of the decision context and CRD needs. Key opportunities, uncertainties, constraints, risks, and vulnerabilities can then be described for the decision context. The main outcomes of this step are a list of goals and targets for AMD, key constraints, climate risk and vulnerability assessments, and a description of relevant uncertainties and opportunities.

Step 2. Envision futures and define strategies.

Bringing together adaptation, mitigation, and sustainable development coherently over time quickly becomes complex, with many possible pathways and interactions. Envisioning different futures can help integrate the three policy objectives and manage this complexity by forming a few coherent visions for the future (van 't Klooster et al., 2024). Moreover, envisioning alternative futures, instead of focusing on preventing risks, has the potential to catalyse transformations towards climate resilient development (Swart et al., 2023).

With the help of ***visioning or "futuring"*** methods (e.g. participatory scenario planning, imaginaries, scenario axes or matrix techniques), various futures are envisaged (Drescher and Skoyles, 2024; López-Rodríguez et al., 2024; Nalau and Cobb, 2022; van 't Klooster and van Asselt, 2006). A subset of these diverse futures are then selected to design pathways towards. The number of futures can be limited to keep the complexity of CRDP measures and pathways manageable. The visioning exercise is conducted with stakeholders, in an inclusive co-creation process to engage diverse voices and support just process and outcomes. Such co-creation settings can bring the values and norms of a variety of stakeholders to the table, including vulnerable groups, aligning with principles of procedural and recognitional justice (Colloff et al., 2021; Schlosberg and Collins, 2014).

Taking together the decision context from Step 1 and the envisioned futures, ***CRD strategies*** are then formulated that describe the directions toward achieving the envisioned CRD futures. For example, a city may choose to elaborate alternative CRD strategies toward a 'green city', a 'high-tech' city, and a 'walkable' city.

Step 3. Map the solution space.

With CRD strategies defined, the solution space, with available AMD options, is mapped by 1) assessing key contextual factors that determine the feasibility of measures, such as socio-political conditions, governance aspects, and laws and regulations, 2) identifying measures and analysing their thresholds to determine when follow-up measures would be needed to be in place and 3) assessing AMD interactions. CRDP particularly emphasizes vulnerability and justice, which must be incorporated while mapping and evaluating the solution space to safeguard just outcomes for all.

The solution space is shaped by ***contextual factors***. Relevant factors can help identify what is feasible and how this can be shaped with additional actions (Haasnoot et al., 2020). The contextual factors can be determined through analysis of policy documents, institutional arrangements, and laws and regulations (see for example Table 2).

As vulnerabilities and opportunities for CRD change over time, new measures are needed. ***Thresholds*** can be used to determine when and under what conditions new actions must be implemented (Haasnoot et al., 2019, 2013; Kwadijk et al., 2010). Adaptive pathways studies typically consider the performance of adaptation measures (e.g. how much sea level rise a measure can protect against), but for CRDP there are additional reasons to implement next measures, such as new targets for mitigation or development, and opportunities that arise when conditions change. We therefore define three types of ***thresholds*** for CRDP, to reflect different conditions or reasons for new or reinforced adaptation, mitigation, or sustainable development action. The first type occurs when a performance threshold is exceeded. This is sometimes referred to as an adaptation tipping point, but here it is also used for sustainable development. Performance thresholds can be identified through sensitivity testing or option valuation, and involve setting clear performance criteria (e.g. acceptable flood levels or temperature thresholds), modelling how the system behaves under a range of future climate and socio-economic scenarios, and identifying the point in time or conditions under which the current measure fails to meet its objectives. The second type of threshold, an opportunity point, occurs when an opportunity arises. This kind of threshold is also used in DAPP. The final type of threshold, proposed specifically for CRDAPP, is a target point, resulting from moving targets. This threshold is introduced to cover policy targets for mitigation and sustainable development (e.g. climate neutrality by 2030), which do not reach performance thresholds like adaptation measures. Instead, target points can guide the selection and timing of measures to reach specified targets. The three types of thresholds are explained in Table 1.

We distinguish three main types of ***interactions*** between adaptation, mitigation and sustainable development measures for CRDP: the feasibility to implement measures together, impacts on the effectiveness of other measures, and side-effects of measures on other objectives. AMD interactions can result in synergies, conflicts, co-benefits and trade-offs.

Feasibility of AMD measures relate to the simultaneous implementation of AMD measures in a constrained space. A synergy occurs when measures can be implemented together, e.g. cool pavements and walkable neighbourhoods. A conflict may arise when pursuing a compact city approach for urban development while simultaneously having sufficient open space for urban greening.

The *effectiveness of AMD measures* refers to the impact of one measure on the effectiveness of another, or when it results in an increased need for measures. Here, synergies occur, for example, when implementing green roofs for urban cooling and flooding also improves building insulation. A conflict may exist between creating a decarbonization zone and installing air-conditioning in houses.

Side-effects of AMD measures occur when a measure is affecting another policy objective or domain (e.g. biodiversity, health etc.). A co-benefit could be if a park for urban heat and flood risk improves biodiversity. A trade-off may be that the green park could result in more insects or animals carrying disease, negatively affecting human health. Furthermore, a lock-in can be regarded as another type of interaction that is related to a sequence of measures over time creating path dependency (see table of definitions in appendix A).

Systematically assessing the AMD interactions can help decision makers to weigh options and inform the implementation of measures. CRDP aim at maximizing positive interactions (e.g. synergies and co-benefits) and minimizing negative ones (e.g. conflicts and trade-offs). Interactions can be assessed in multiple ways and various rudimentary tools exist, e.g. C40′s Adaptation and Mitigation Interaction Assessment tool and the SDG Climate Action Nexus tool (AMIA, 2024; SCAN-Tool, 2024). Co-design approaches, such as group model building and system dynamics can also support this kind of analysis. In our case study (Section 3) we present two qualitative means to assess feasibility, effectiveness and side-effects, respectively, through the AMD interactions triangle, and a side-effects table.

Step 4. Design and evaluate pathways.

Close and regular engagement with relevant stakeholders is central to co-creating and evaluating the pathways. The key components of the pathways are developed in Steps 1 to 3. The measures described in the current policy (Step 1) offer the starting point for building the pathways, with additional and alternative measures identified when mapping the solution space (Step 3). The selected futures and associated CRD strategies (Step 2) guide which measures are developed into specific pathways. The pathways are structured by the thresholds (Step 3), which indicate the point at which a new measure must be in place. This may involve a new measure within the same pathway or a transfer to another pathway. The new measure or transfer must be implemented before a threshold is reached (Step 3). While designing pathways, interactions between measures need to be considered, ideally maximizing positive interactions (synergies and co-benefits) and minimizing negative interactions (conflicts and trade-offs) (Step 3).

Table 1
The three types of thresholds for CRDP, including their definitions, and examples; performance threshold (PT), target point (TP) and opportunity point (OP).

Threshold type	Reasons for new measures (thresholds)	Typical for A, M, or D	Example
Performance thresholds (PT)	Occurs when the magnitude of change is such that a current management strategy can no longer meet its objectives, which is often occurring in the context of risk reduction. As a result, management is needed to prevent or postpone these PTs. The effectiveness of the measure or set of measures to reduce risk should be assessed to identify the performance threshold. Similar to adaptation tipping point (Haasnoot et al., 2019; Kwadijk et al., 2010).	Adaptation (A)	A flood wall that is no longer viable in 2050 due to sea level rise.
Target points (TP)	Occurs when the current management strategy has attained, or is unable to meet, its time-dependent targets and/or when a new target is defined. Consequently, enhanced or new measures are needed to meet the (new) target. To identify the target point, the effectiveness of the measure(s) to achieve the target should be assessed. An unmanageable magnitude of (climate) change or inaction can result in not attaining a target.	Mitigation and Sustainable Development (M, D)	A city's target to reach carbon neutrality by 2030.
Opportunity points (OP)	Arises from windows of opportunity at which a particular action becomes feasible or attractive, for example because of lower costs, change of societal acceptance, or technical developments (Haasnoot et al., 2019).	Adaptation, Mitigation and Sustainable Development (A, M, D)	Carbon-capture and storage technologies becoming available and cost-effective.

A phased approach to designing pathways can help to manage the complexity (Fant et al., 2025; Schlumberger et al., 2022). For example, separate pathways could first be created for mitigation, adaptation, and sustainable development, before examining their interdependence. Alternatively, integrated pathways can be created for each future and respective strategy, and thereafter combined in a larger pathways map or plan.

CRD scenarios are used to evaluate the performance of different CRD pathways over time, to support flexible and adaptive plans. Stress testing pathways with different scenarios helps to assess their sensitivity and robustness to a range of future conditions (Haasnoot et al., 2019, 2015; van 't Klooster et al., 2024). For CRDP, the scenarios can consider climate change (e.g. SLR/heat/precipitation extremes etc.), likelihood of attaining mitigation targets and/or goals, and socio-economic factors (e.g. population change) (Haasnoot et al., 2019, 2015). Scenarios can use values or relative scales, such as "slow", "moderate", "fast" to denote different pace or amount of change and can be based on climate and socioeconomic scenarios, such as Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathway (SSP) (van Vuuren et al., 2014, 2011).

Pivotal decisions can be identified from the pathways. Pivotal decisions are critical choices that significantly influence available options for the future and may create path dependencies (Hanger-Kopp et al., 2022), particularly, in balancing or prioritizing CRD objectives across different future visions.

For CRDP, the interactions are evaluated among the different pathways for the selected measures to provide knowledge about the key positive and negative interactions, to be considered by decision makers in the planning and implementation process. Further evaluation of the pathways could be done through a number of methods, for instance a scorecard summarizing all positive and negative interactions for feasibility, effectiveness and the side-effects; a cost-benefit analysis of measures; the social impacts of the pathways (including distributional impacts related to justice); a political feasibility assessment; and/or through a stakeholder evaluation.

Step 5. Design an adaptive plan.

Similar to the DAPP approach and based on the evaluation of the pathways (Step 4), short and long-term measures are identified, including "low regret" measures, that could benefit all or most pathways, keeping options open for the longer-term. Also similar to DAPP, adaptive CRD plans contain short-term actions for implementation and preparation for the long-term options. In addition, an adaptive plan includes a monitoring system, specifying the process, as well as indicators for key changes and developments to track. For CRDP, a wide set of information is required for tracking not only progress of adaptation, mitigation and sustainable development, but also tracking changes that may require adjustment to the adaptive pathways plan or acceleration of implementation. Insights on climate change, socio-political developments, distributional impacts related to vulnerability and justice, governance, economic changes, societal values and technical innovations can be informative for this. For each of these changes indicators to monitor need to be identified (e.g. number of heatwaves for heat stress, rate of sea level rise, pace of emissions reductions, housing demand). These indicators need to be translated into (early warning) signals and triggers. Signals indicate that a threshold or target point is approaching. Trigger values instigate a decision with sufficient time for the preparation and implementation of next measures, before the threshold is reached (Haasnoot et al., 2019, 2018; Lawrence et al., 2018).

Step 6. Implement plan and Step 7. Monitor plan.

The implementation of the adaptive plan can now start, with initial measures implemented immediately or in the near-term. CRDAPP pathways should form part of a broader CRDP planning process or transition. Explicit consideration to organisational and sectoral barriers and silos, and how to overcome them will support effective implementation of the actions. Governance aspects, such as institutional capacity and complexity, political agency, and power dynamics are crucial for implementing measures in reality. The pathways are continuously monitored to track progress and ensure timely adjustments of the pathways and/or to stay on track and seize opportunities. Based on new information and/or changing conditions, thresholds may occur earlier or later than initially identified, which informs the pace of implementation and could require adjustments of the pathways.

In line with DAPP, CRDAPP can be conducted at three levels of analysis (Fant et al., 2025; Haasnoot et al., 2019) or combinations of these levels: 1) qualitative and narrative-based, relying largely on stakeholder knowledge, 2) (semi-)quantitative or expert-based, adding existing information, expert opinion, simple models and generic tools to stakeholder knowledge; and 3) fully quantitative, or model-based assessments with stakeholder knowledge. Concerning the role of stakeholders in each of the seven steps, it is crucial that the pathways are co-created in a participatory planning process that is grounded in local knowledge and diverse perspectives to enable a just procedure and outcomes. Further, while this process supports decision analysis, fully developing CRDP will require engaging complementary evaluation tools to support elements not addressed by CRDAPP.

3. Demonstrating the CRDAPP approach with an illustrative case study in Cork City, Ireland

To demonstrate the applicability of CRDAPP, an illustrative and qualitative case study is presented for the city of Cork in Ireland, as a level 1 analysis (see prior paragraph). A city was selected to test the approach, as urban areas are hotspots for climate action and sustainable development (Rosenzweig et al., 2018; UN, 2023; UN-HABITAT, 2024), and therefore a suitable testbed for CRDP. In particular, Cork City was selected as an exploratory case study because it faces challenges and opportunities with respect to long-term planning for all three AMD objectives. The city is a signatory of the EU Missions on Adaptation and on Climate Neutral and Smart Cities, and is on track to be the fastest growing city in Ireland, creating large ambitions for adaptation, mitigation and development. The CRDP approach also aligns with policies of the Irish national authorities, who have embraced adaptive pathways planning and encourages local authorities to use it for their policy plans (Government of Ireland, 2024). Cork City officials and stakeholders expressed interest in exploring adaptive pathways planning to support ongoing climate action and sustainable development efforts in the city.

For the qualitative case study in Cork City, we focus on those elements that are particularly novel and different compared to DAPP: formulating different CRD strategies; assessing AMD interactions between measures; identifying thresholds; creating integrated pathways; identifying pivotal decisions for the pathways; evaluating the pathways based on AMD interactions; and identifying indicators to monitor to derive signals and triggers. Cork City Council (CCC) is active in adaptation, mitigation and urban development planning. Piloting CRDAPP is not part of the City Council's official planning process. However, the pathways development was informed by multiple site-visits to explore the city and understand the local planning context, and by engagement with local and national level stakeholders responsible for mitigation, adaptation and urban development. Two in-person workshops with stakeholders, including policymakers, urban planners, community engagement officers and climate scientists, were held in Cork City to discuss and evaluate the pathways, as well as to assess the AMD interactions and to understand challenges that could arise as a result of specific measure implementation. In addition, the initial concept of the pathways approach was presented and discussed in a workshop with representatives from academia, local and national government, industry and civil society. The co-development process is described in more detail in McCullagh et al., 2024). Community engagement was not part of this case study, because it was exploratory in nature and did not form part of the city's formal planning process.

3.1. Cork's decision context (Step 1)

Cork is a historic city built on marshlands in an extensive estuary of the river Lee with a natural harbour. Cork City is the second largest and fastest growing city in the Republic of Ireland, with a population of 211,000 people. Demographic projections indicate a ~60 % population increase by 2040 (CCC, 2022). Situated at the coastline, as well as along the river Lee, Cork is heavily impacted by frequent fluvial and tidal flooding. In November 2009 large parts of the city were flooded due to periods of extended rainfall and insufficient flood management, causing

€90 M damage (Jeffers, 2011; Nash et al., 2018; Walsh, 2010). A severe tidal flood in February 2014 led to €40 M in damages (Grath, 2015). The social vulnerability mapping for Cork City (Appendix B) indicates that the most vulnerable populations predominantly live in flood-prone areas in the city centre and south of the city centre and of the river Lee (Fitton et al., 2022; McCullagh et al., 2025). Additionally, Cork is increasingly exposed to heat extremes, with negative health effects on the population, particularly the elderly and children (CCC, 2023).

Climate change projections indicate that rainfall will most likely increase in winter and decrease in summer and will become more variable with dry periods and heavy precipitation events, resulting in more flooding events. Sea levels have risen by 0.16 m since 1902 at the coast around Cork. A further increase is projected between 0.32–0.6 m (RCP2.6) to 0.63–1.01 m (RCP8.5) by 2100, intensifying tidal flooding. Mean temperatures increased by 0.9 °C during the last 120 years. The 15 top warmest years occurred since 1990. A temperature increase of 0.44–1.10 °C (RCP2.6) to 1.18 °C-2.10 °C (RCP8.5) is projected for 2041–2060, relative to 1976–2005. Heat waves and extremes are projected to become more intense and frequent in the upcoming decades (CCC, 2023; IPCC, 2021; O'Brien and Nolan, 2023).

Cork City Council as well as other Irish institutions on the regional and national level have formulated extensive plans and policy documents to deal with and prepare for changes in climate and its related impacts, as well as demographic changes and sustainable development (see overview of policy plans and documents in Appendix C). The Lower Lee Flood Relief Scheme (LLFRS) together with other plans aim to reduce flood risks and protect the city from on-going and future fluvial and tidal flooding events (OPW, 2020). The recent draft Climate Action Plan 2024–2029 specifies goals and respective measures for mitigation and adaptation (CCC, 2023). Cork is one of the 100 climate neutral and smart cities of the EU Cities Mission, and is therefore committed to become climate neutral by 2030. To deal with the expected population growth the Urban Development Plan outlines how the former industrial harbour areas (Docklands) and other brownfield sites throughout the city will be regenerated. Based on these policy plans and documents, as well as stakeholder interactions and site-visits, the key goals with respect to adaptation, mitigation and sustainable development are formulated, and a sub-selection of the main AMD measures within these policy plans are mapped (Fig. 2). The existing goals and associated measures form the basis for the assessment of thresholds, as well as to construct futures and associated strategies.

3.2. Different futures and associated strategies for Cork (Step 2)

Different climate resilient futures for Cork City are envisioned and main strategies towards those futures identified. To cover a broad range of potential future states for Cork, two opposite alternatives for each CRD objective are defined based on the policy document analysis and stakeholder engagement in Step 1 (Fig. 3). For flood adaptation we distinguish a future that fully protects Cork City from all flooding at the far left, and at the far right the option to accommodate flooding. For mitigation, there can be a focus on technological options (tech-fix) or on green and circular solutions. This axis is also applicable for adaptation to heat and flood. The third axis corresponds to the urban development and influx of population that Cork is expecting to face in the coming decades. For urban development, a spectrum ranging from a compact city to urban sprawl is indicated. Logical combinations between the three axes form the main integrated CRD strategies to build climate resilient development pathways (Fig. 3). Even though other combinations of CRD strategies are possible, we selected three CRD strategies that allow us to explore a wide range of potential future states for Cork City, integrating adaptation, mitigation and sustainable development. The three different futures and related CRD strategies were discussed in a co-development workshop in Cork City and are indicated in Fig. 3 along the axes,

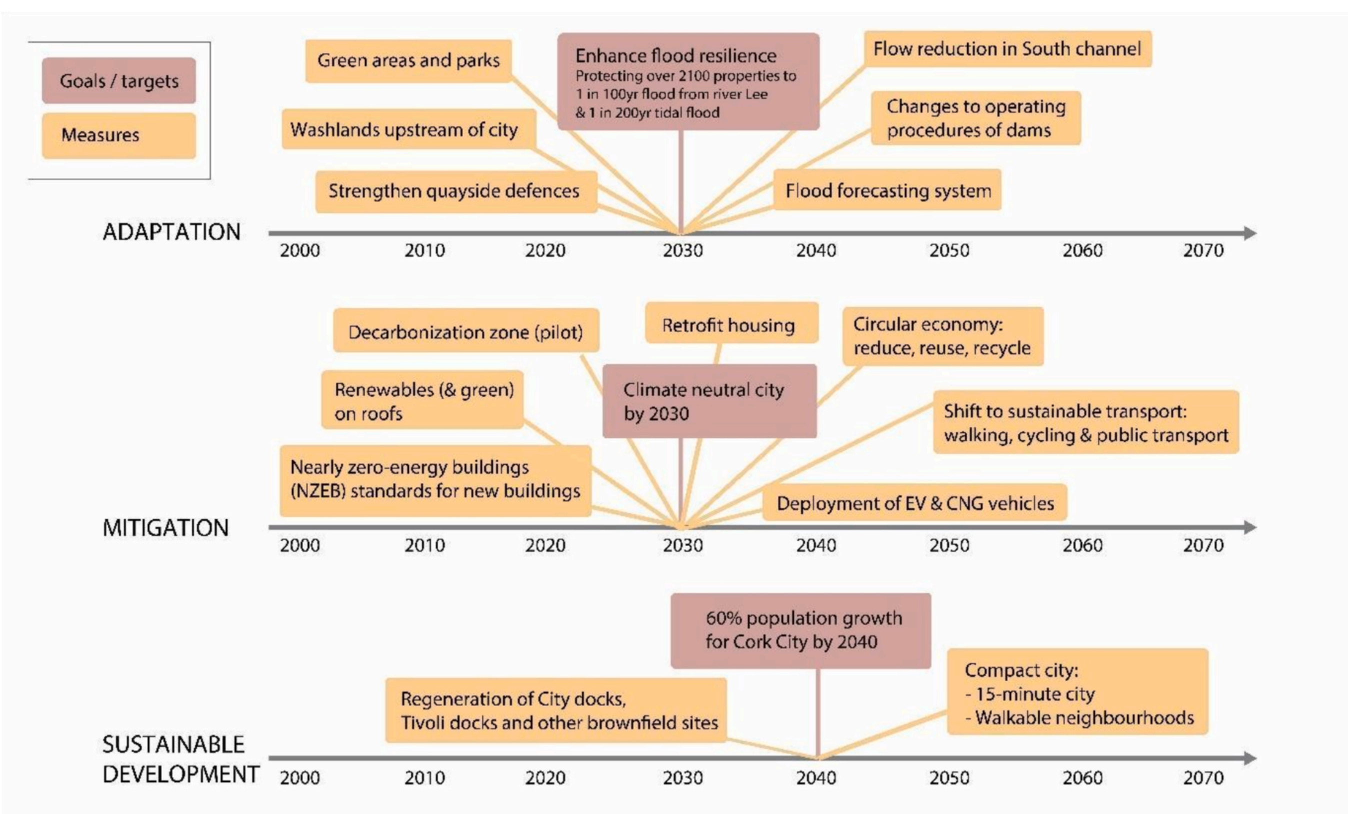

Fig. 2. Overview of key targets, goals and measures as described in current policy documents for adaptation, mitigation, and sustainable development for Cork City, Ireland.

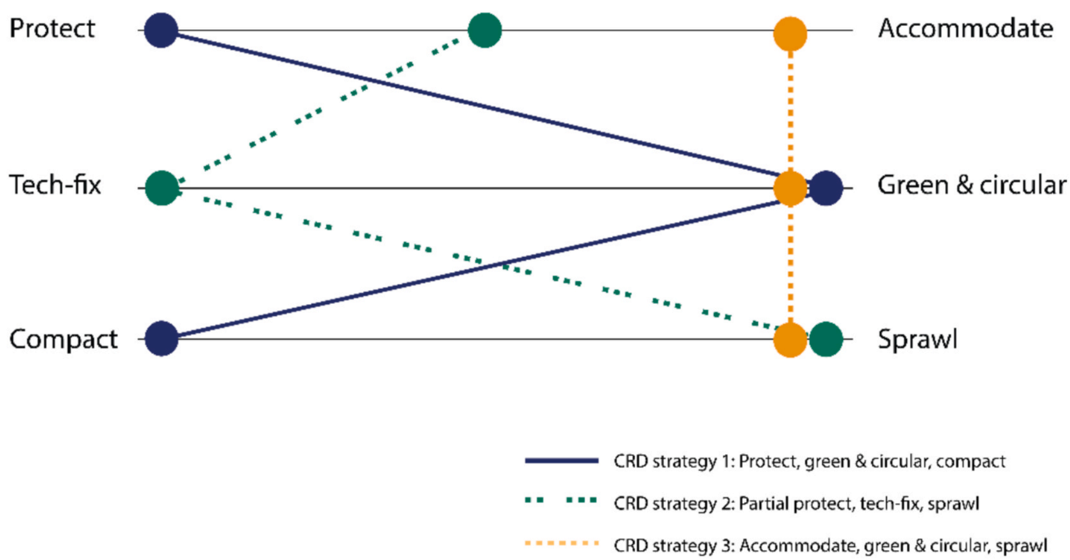

Fig. 3. Three different CRD strategies for Cork City (1. blue-purple solid line, 2. green dashed line with gaps, 3. orange full dashed line), integrating the three policy objectives adaptation, mitigation, and sustainable development. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

respectively: 1) Protect, green and circular, compact (blue-purple, solid line); 2) Partial-protect, tech-fix, sprawl (green, dashed line with gaps); and 3) Accommodate, green and circular, sprawl (orange, full dashed line).

3.3. Cork's CRD measures and their interactions and thresholds (Step 3)

The solution space for Cork City provides insights into available measures, the opportunities and constraints for pursuing action towards climate resilient development. For instance, the solution space in Cork could be enlarged when a political party is elected with climate change action high on their agenda. A shift from cars to more sustainable means of transport requires behavioural changes, which might be challenging in Cork as it is a car-minded society – narrowing the solution space. Based on the policy document analysis, literature, and interactions with city stakeholders, the key contextual factors that determine whether measures are feasible for Cork City are summarized in Table 2, including political context, governance and economic aspects, laws and regulations, and projected climate change impacts.

Cork City currently plans a wide collection of AMD measures, as indicated in Section 3.1 and Fig. 2. The longer-term effectiveness of these measures are assessed to determine their relative thresholds (e.g. short, medium, long term) based on the explicit targets of Cork City, literature review, and expert judgement. In a more comprehensive (quantitative) analysis, the effectiveness needs to be further assessed against a range of future scenarios. A target point for mitigation is projected in 2030, based on the EU mission on Climate Neutral and Smart Cities commitment to become climate neutral by 2030. A performance threshold for the Lower Lee Flood Relief Scheme is estimated for the mid-to-long term, based on calculations by the national Office of Public Works (OPW) (OPW, 2020). The goal to accommodate 60 % population growth by 2040 is a development target point. One opportunity point could arise from small-scale, site-specific carbon capture and storage technologies, e.g. for industrial sites and the harbour. This is a new technology that could become more attractive in terms of cost efficiency and implementation (Table 2) (Caparros-Midwood et al., 2019). This technology could be installed in the near-term, after the current 2030 target point for mitigation. Additional opportunity points are likely to emerge for Cork City in the future. Early detection through monitoring of signals and identifying triggers will be important.

For the additional measures identified, thresholds can also be assessed. After 2030 it would be likely that a new mitigation target will be set or the current timeline may be extended for becoming climate neutral. Performance thresholds for high quayside defences and large-scale flood detention areas are expected on the mid-to-long term under all climate change scenarios. With rising sea levels, a tidal barrier could offer long-term protection for Cork City, if retreat is not preferred. However, like all protection options, a tidal barrier's effectiveness is subject to the rate and magnitude of sea level rise. In addition, performance thresholds are expected for heat adaptation strategies in the near-to-mid-term while temperatures and extreme heat episodes increase, and because Cork City has not been planning heat adaptation measures until recently.

The interactions between AMD measures are mapped for the sub-selection of measures included in the current policy documents (Section 3.1, Fig. 2) and for the additional actions for adaptation, mitigation, and sustainable development beyond the existing policies and plans. The mapping is based on literature, expert judgement and evaluation during stakeholder workshops. The AMD interactions triangle identifies potential synergies and conflicts between measures accounting for the feasibility and effectiveness of interactions (see definitions in Section 2, Step 3), as shown in Fig. 4. The additional measures are presented in grey text in Fig. 4 and in Appendix D. The interactions are heavily dependent on the location where the city government plans the measures and also how they are implemented. For instance, the quayside defences can be designed not only to protect against flooding but also to provide a cool public space, a recreational area and sustainable transport route supporting mitigation and development objectives. "Walkable neighbourhoods" stands out as a measure with various synergies and no conflicts. Multiple adaptation measures could conflict with the circular economy as adopted by Cork City Council, particularly measures such as pumps and air-conditioning, which are energy intensive to manufacture and operate. Both walkable neighbourhoods and decarbonization zones show mainly synergies with other AMD measures. The co-benefits and trade-offs of the measures on other policy objectives are assessed and presented in appendix D. Further policy objectives could be added beyond biodiversity, air quality, health and wellbeing. In line with literature (e.g. Sharifi, 2021), green areas and green roofs show most co-benefits for the city of Cork.

Table 2
Key factors influencing the solution space in Cork City.

Key factors influencing solution space	Short description for Cork City
Political context	• Plans outlining flood relief schemes, as well as a climate action plan and an urban development plan have been developed by Cork City Council and the national entity responsible for water management, the Office of Public Works (OPW). • The Cork City Council is currently focused on implementing the plans for the coming 4–8 years. • The issues around flooding and respective relief measures are sensitive within the city and constrains the willingness and possibility for further flood adaptation action setting. • Policy planning occurs at the national, county and city levels, with interlinked goals and actions.
Standards and regulations	• Standards for flood protection: 1 in 100yrs by river, 1 in 200yrs from tide (by Office of Public Works, OPW). • Cork City is selected for the EU Mission on Climate Neutral and Smart Cities, with the associated target to become a climate neutral city by 2030.
Civil society and norms, values, interests of inhabitants	• Flooding is a prominent problem for inhabitants, with many having experienced the impacts of floods directly. • There is an active civil society group who wish to keep the historical Cork City as it is, and therefore counteract flood relief schemes and other measures proposed by the City Council that may change the look and feel of the city. • Cork City is a car-oriented society, which makes it harder to change to other means of transport such as bicycles, public transport or walking.
Economy	• The economy is focused on commerce and professional services – with particularly strong ICT and pharmaceutical sectors – and to lesser extent manufacturing. • Cork City is mandated by the National Planning Framework to be the fastest growing city in Ireland to provide a counterbalance to the dominance of Dublin. • Affordability and availability of housing is an ongoing and growing challenge, particularly in the light of the projected population growth. • In 2024 Cork was ranked the number one small city in Europe for Foreign Direct Investment strategy and second for economic potential (European Cities and Regions of the Future Rankings). • Large investments are ongoing and expected in transport infrastructure and housing, e.g. 3.5 billion]in the transport infrastructure including the delivery of a cross city tram system and 1.9 billion to be invested in housing by 2026 with minimum energy ratings of A2.
Equity and justice	• Vulnerable populations are currently living in flood-prone areas, mainly south of the city center and of the river Lee, and in the city center (Appendix B). • Cork City Council closely considers vulnerable areas for planning adaptation measures to protect the more vulnerable against flooding, as a part of their just transition approach to climate action.
Technological innovation	• Smaller site-specific carbon capture technologies (e.g. on industrial sites and the harbor) become available to cities (Caparros-Midwood et al., 2019). Carbon may then be stored in the Cork County storage project that is under development at Kinsale Head.
Climate change impacts	• Heavy precipitation extremes, particularly causing fluvial and pluvial flooding. • Slow-onset sea level rise and storm surges. • Fast sea level rise, e.g. due to global ice sheet and glacier melt. • Rate of climate change, particularly depending on global mitigation efforts.

3.4. Climate resilient development pathways for Cork City

The CRD pathways map (Fig. 5) shows the range of options and possible pathways for adaptation, mitigation and development. It also shows the three main sets of pathways to achieve each CRD strategy (Fig. 5, respectively upper and bottom panel). The pathways map was generated by taking the measures already planned in the city's current policy, and alternative measures identified in this study, alongside their assessed interactions and thresholds. The AMD measures were combined and sequenced over time into pathways that aligned with the defined CRD strategies (Step 1–3, Section 3.1 – 3.3). The portfolio of measures is listed along the vertical axis of the pathways map (Fig. 5) and grouped for adaptation, mitigation, and sustainable development to maintain a clear overview. An indication is provided until when each measure could work, based on the threshold assessment (Section 3.3). Narratives for the three main CRD strategies and the respective pathways are described in appendix E. All CRD pathways start with measures that are included in current Cork City Council policies, including the Draft Climate Action Plan 2024–2029 (CCC, 2023), the Lower Lee Flood Relief Scheme (OPW, 2020), and the Urban Development Plan (CCC, 2022).

Key differences and similarities between the three main CRD strategies and associated pathways can be identified (Fig. 5). For mitigation, a decision arises between the different CRD strategies after the near-term target point (2030), when a new mitigation target and action setting is expected. At this point, the pathway underpinning CRD strategy 2 (tech-fix) employs site-specific carbon capture and storage (CCS) (opportunity point) and emphasizes renewables on roofs as well as electric and CNG vehicles in the near-to-mid-term. By contrast, the pathways supporting CRD strategy 1 and 3, reinforce the existing climate action plan measures and multiply the decarbonization zones after the 2030 target point. For heat adaptation, a similar difference is found, with the pathway for strategy 2 focusing on tech-fixes (e.g. air conditioning) and pathways for strategy 1 and 3 on green/blue measures. As part of the three different CRD strategies, some of the Lower Lee Flood Relief Scheme measures will remain effective for flood adaptation on the mid-to-long term (such as the early warning system and river regulation). Other measures will be useful but no longer offer sufficient protection to flooding in the mid-term (performance threshold), given rising sea levels and increased heavy precipitation in winter. This is particularly the case in the city centre and the planned regeneration districts in the dockland areas. The pathways working towards strategy 1 and 2, both require increasing the quayside defences, a tidal barrier and large pumps in the long-term to protect Cork City from flooding. However, there is some flexibility to switch between strategy 1 and 2 in the mid-to-long term. A choice exists between strategies 1 and 2, or transferring to strategy 3. The latter opts for partial retreat in the long-term, refraining from building large flood adaptation infrastructure, such as pumps and a tidal barrier. For sustainable development, the critical difference and transfer between the strategies arises in the near-term, in deciding whether to regenerate the dockland areas. The pathway for strategy 1 follows a compact city approach and fully regenerates the dockland areas. The pathway for strategy 2 only partly regenerates the docklands and elevates and floodproofs buildings. The pathway underpinning strategy 3 prepares for partial retreat and builds at the city edges instead of in the docklands.

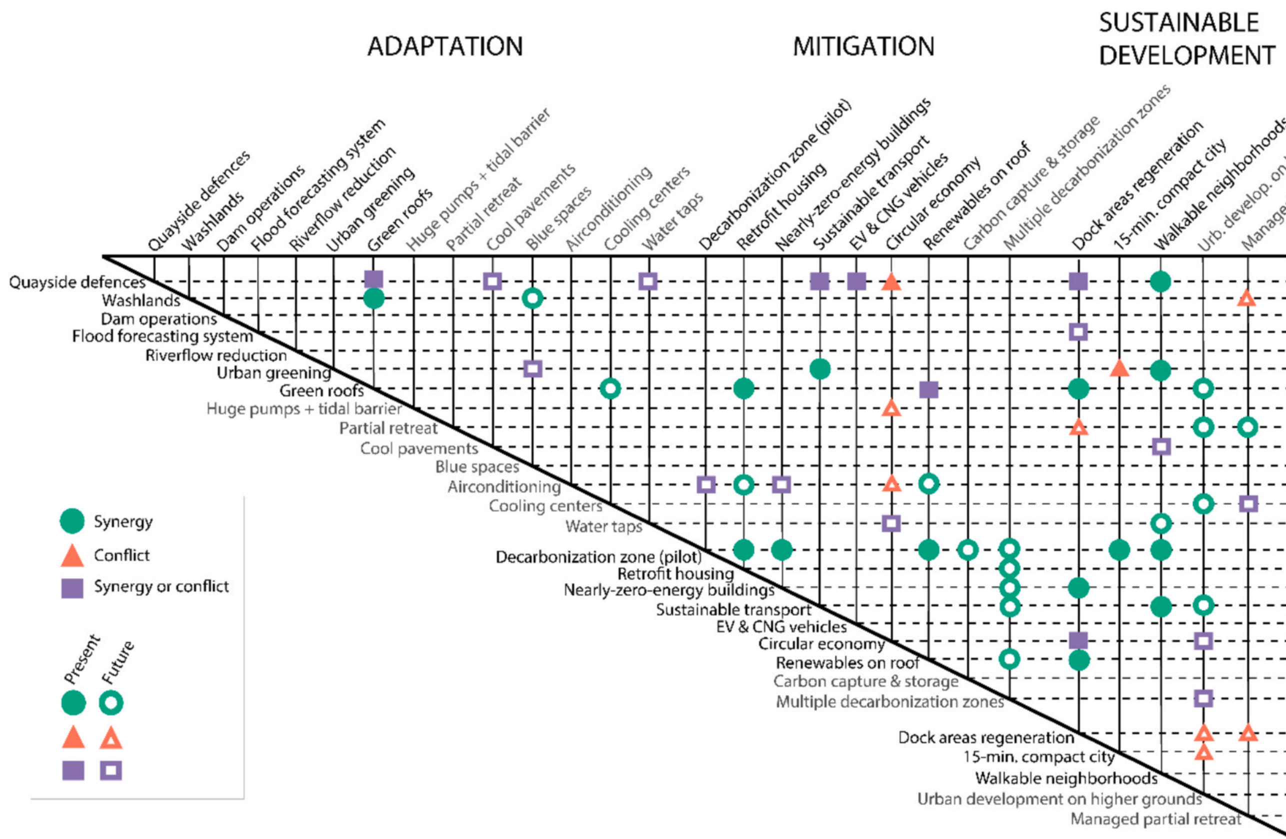

Fig. 4. Adaptation, mitigation, and sustainable development (AMD) interactions triangle. Systematic identification of interactions (effectiveness and feasibility) between AMD measures. Completed as an illustrative example for Cork City. The green dots reflect a potential synergy between two measures and the red triangles indicate a conflict. The purple squares indicate that either a synergy or conflict could arise. Showing the measures from the current policy (black) and for alternative future measures (grey). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The key differences between the three main pathways and the interdependencies of mitigation, adaptation and sustainable development measures over time can be translated into pivotal decisions, to support decision making. Fig. 6 shows these **pivotal decisions** for the different CRD strategies and highlights their path dependencies:

1. In the near-term, a pivotal decision arises about the dock areas regeneration: whether to pursue a full regeneration development, a partial and elevated regeneration, or to decide not to build in the docklands.
2. In the near to mid-term, a critical junction around the trajectory of mitigation and heat adaptation is expected. A more tech-fix approach could be followed (including CCS, air conditioning etc.) or a more green-circular approach could be pursued (green areas/roofs, blue spaces etc.). Relying on traditional air conditioning would create conflicts for mitigation objectives.
3. In the long-term, a pivotal decision about building a tidal barrier or partial retreat is expected. It is critical to note that this decision requires a substantial lead-time to prepare the associated actions.

These pivotal decisions highlight important interdependencies between adaptation, mitigation and sustainable development measures (Fig. 6, as well as the green vertical lines in Fig. 5). One key decision is if the city further regenerates the flood-prone docklands to maintain a compact city (CRD strategy 1 and 2), or if new buildings are constructed on higher grounds at the edges of the city (CRD strategy 3). The decision to fully or even partly regenerate the docklands could create a lock-in situation, where the city would have to continue to protect inhabitants and businesses in the area under increasing flood risk. This would include funding the construction of large-scale interventions like pumps and a tidal barrier, and associated maintenance costs. These pivotal decisions also highlight time dependencies between AMD measures. For example, taking the decision now to regenerate the docklands implies a long-term need for flood adaptation measures.

Qualitative, narrative-based CRD scenarios are developed to check the sensitivity of options to different futures and to understand how uncertainties may influence the pathways, including: 1) flood risk and needed adaptation – the rate of change in sea level, precipitation and temperatures under climate change (moderate vs. fast); 2) mitigation – the rate at which local GHG emissions are reduced over time (e.g. moderate or fast); 3) housing, services and work needs – how the influx and growth of the population evolves (moderate vs. fast).

The evolution of the scenarios influences thresholds and pathways. For instance, if the rate of climate change is fast, causing a rapid increase in flood risk, then the performance threshold for the Lower Lee Flood Relief Scheme could be reached sooner, and switching to new measures would be required earlier. In case of high-end and rapid sea level rise, some adaptation options may no longer be feasible at all. If GHG emissions reduction measures are highly effective in Cork City, next mitigation targets will not be needed, but delays in achieving the current target would require new measures. The expected influx of new inhabitants could be lower or higher than projected, or occur in specific time windows, requiring adjustments to the rate and amount of housing needed. There are also interdependencies between these uncertainties and the AMD measures. As an example, if both the rate of climate change and the influx of people are fast, then quick action is needed to build housing and implement adaptation measures, potentially putting pressure on city authorities and resources. By contrast, if the influx of people is fast, but climate change is slow, then regenerating the docklands becomes more attractive.

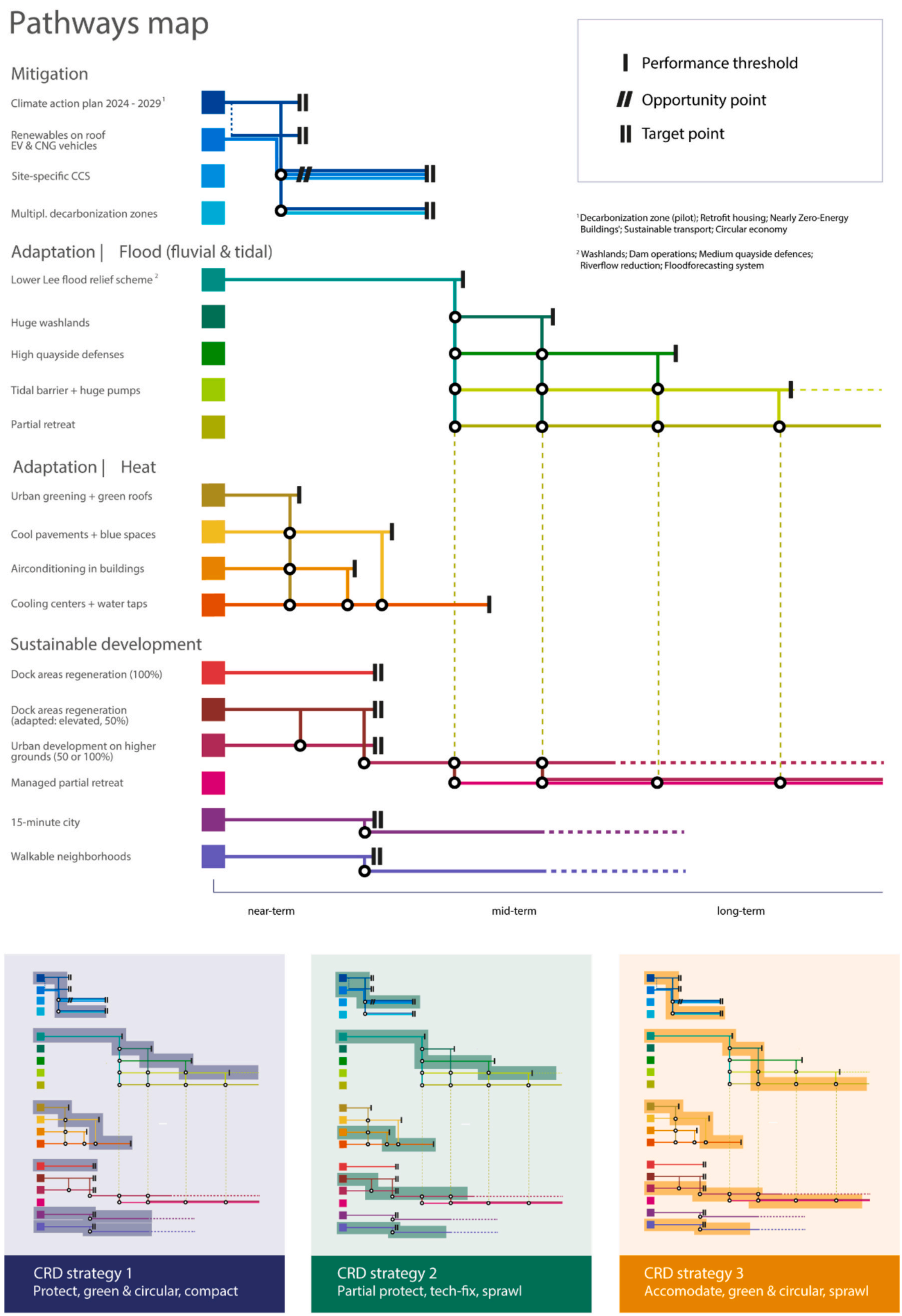

Fig. 5. Climate resilient development pathways map for Cork for the three policy objectives, adaptation, mitigation, and sustainable development. The pathways for the three CRD strategies are indicated in the three sub-panels on the bottom, in blue, green and orange, the highlighted pathways are included in the strategy. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

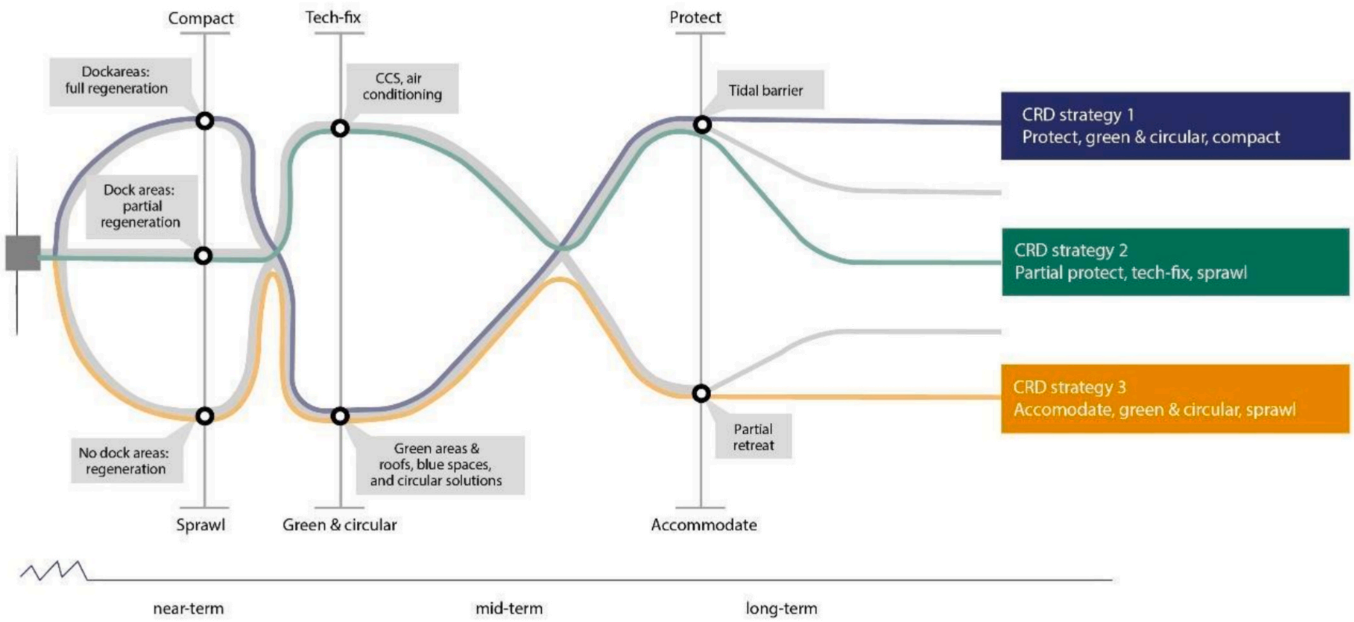

Fig. 6. Pivotal decisions for the different climate resilient development pathways towards the three CRD strategies.

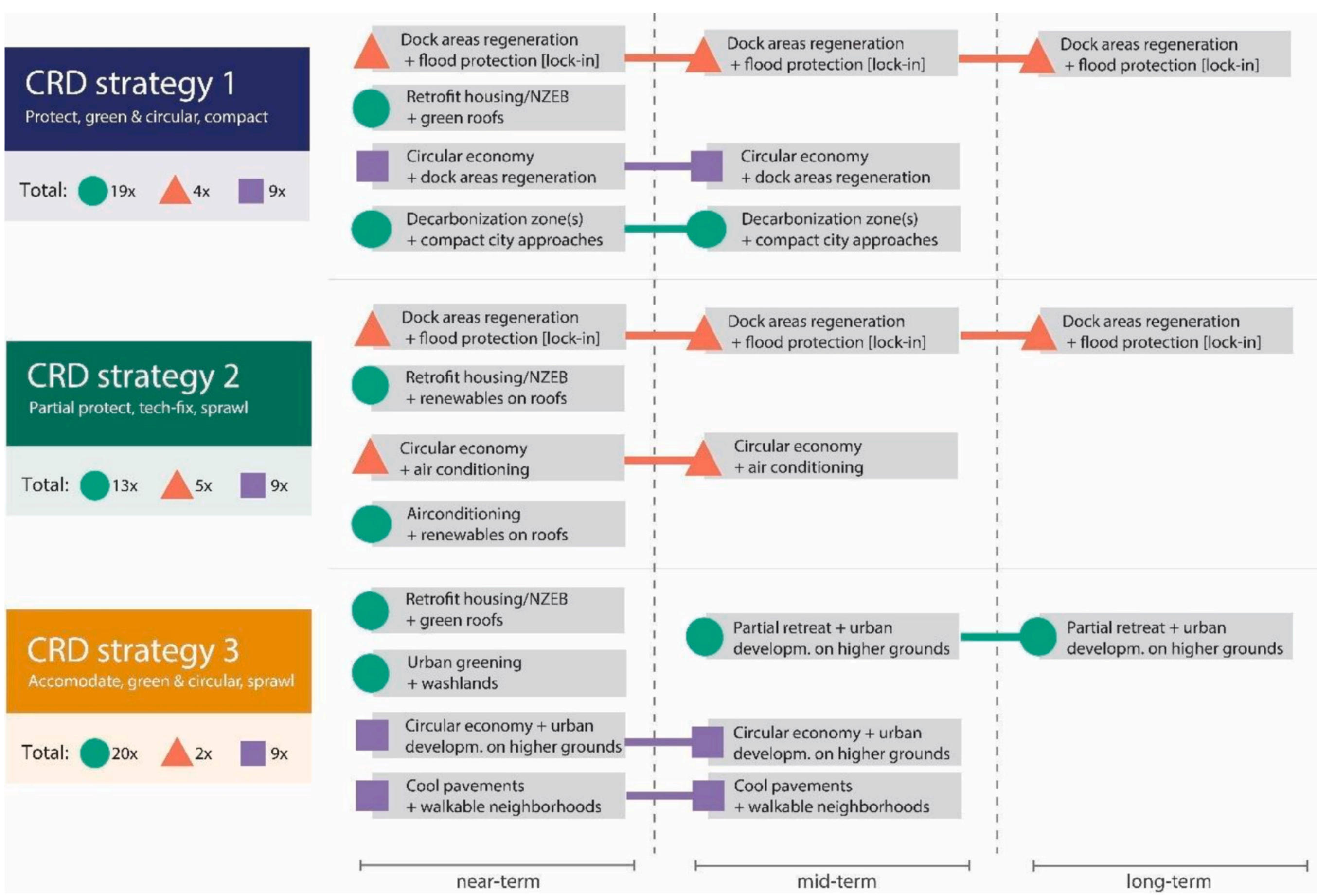

Fig. 7. Evaluation of selected interactions within each pathway underpinning a CRD strategy. The interactions include both feasibility and effectiveness between different measures over time (near-, mid- and long-term), showing synergies (green circle), conflicts (red triangle), or either a synergy or conflict (purple square). The total amount of interactions is presented in the sub-box for each CRD strategy. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

To compare the synergies and conflicts for each of the three CRD strategies and identify lock-ins, we assessed the key interactions between measures over time, based on Step 3 (Fig. 7).

CRD strategy 3 shows the most synergies between AMD measures and the least conflicts. CRD strategy 2 shows the least synergies and most conflicts. All three CRD strategies show equal amounts of measures that could result in a synergy or a conflict, depending on the implementation. Nevertheless, a specific interaction between two measures could outweigh the total number of interactions per strategy. CRD strategy 1 and CRD Strategy 2 result in a lock-in with the docklands area regeneration, providing a need for protection from flooding in near, mid, and long term. Decision makers should be aware of this if choosing this measure. All pathways show high numbers of interactions in the near term, compared to further in the future. This is possibly due to high amounts of measures in the current plans for Cork City. The implications are that decision makers should carefully consider if the measures they implement in the near-term may offer synergies and co-benefits, or create conflicts and trade-offs with other policy objectives, now and in the future.

Evaluating the pathways on **side-effects** for various policy objectives is conducted by aggregating the co-benefits and trade-offs of each measure for each main CRD strategy (Fig. 8), using the side-effects table (Appendix E). CRD strategy 1 and CRD strategy 3 demonstrate the most co-benefits, probably due to both strategies following green and circular options. In direct contrast, CRD strategy 2 shows the least co-benefits, probably due to its tech-fix approach. The CRD strategy 3 particularly stands out with a trade-off regarding social stability, due to the "managed retreat" measure. All three CRD strategies result in mainly co-benefits regarding health and wellbeing.

The illustrative example for designing CRDP for Cork City focuses its pathways evaluation on AMD interactions. The pathways were also evaluated during a workshop with city stakeholders. Nevertheless, further evaluation of the pathways would be useful and could be done through economic and social impact assessments of pathways (including vulnerability and justice perspectives), via political feasibility and institutional assessments, and more in-depth stakeholder evaluations, to name a few (de Ruig et al., 2019; Filho et al., 2021; Haasnoot et al., 2020; Stringer et al., 2022; Stroombergen and Lawrence, 2022; van der Brugge and Roosjen, 2015).

3.5. *Designing an adaptive plan, including implementation and monitoring*

An adaptive plan outlines the key measures to be implemented in the short-term, as well as long-term options, for the three CRD strategies. In the illustrative case for Cork City, a no-regret measure is walkable neighbourhoods, as this measure occurs in all pathways and mainly shows positive interactions with other measures. A key decision is centred around how/if to regenerate the docklands, and to what extent these newly constructed buildings should be elevated and/or flood proofed. The implementation plan indicates who, how, and under what conditions implementation of measures happens in Cork City, but this is beyond the current illustrative case.

A monitoring system for Cork City needs a framework to embed key responsibilities for main actors, and an accountability system. The monitoring system derives signals for plan reassessment or triggers for further implementation. For CRDAPP, this includes indicators for AMD, e.g. about mitigation progress (e.g. on the 2030 climate neutrality target), the performance of adaptation measures (e.g. the Lower Lee Flood Relief Scheme and related the river discharge and sea level rise), and advances in sustainable development (e.g. the construction of housing and the actual influx of population). In addition, indicators for vulnerability and justice, and the distributional impacts of measures should be incorporated. Cork's monitoring system should also

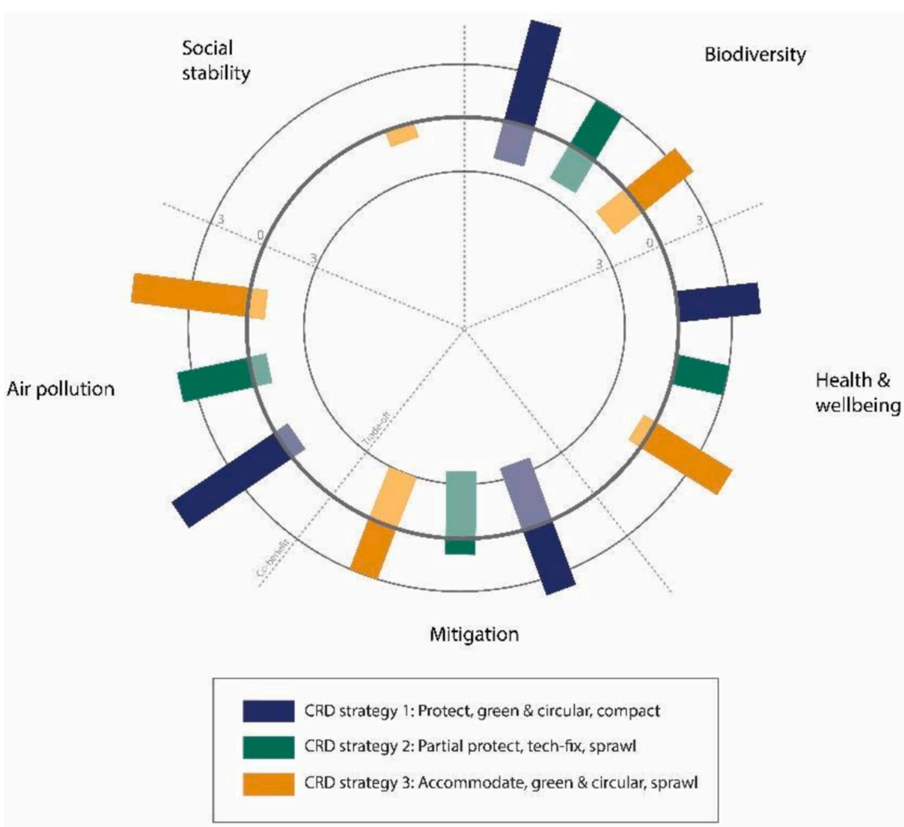

Fig. 8. Evaluation of the pathways on side-effects assessed by aggregating impacts of measures per pathway for each of the main CRD strategies, showing co-benefits (full colour, outer circle) and trade-offs (semi-transparent colour, inner circle).

encompass an annual evaluation of progress on the pathways, and the associated indicators and signals by stakeholders, including the Cork City Council, OPW, citizens, representative citizen groups, etc. The monitoring system and the stakeholder evaluation group could be tied with existing structures dealing with climate change aspects in Ireland on the regional and national levels, such as the Irish Climate Action Regional Offices (CARO's) and the Climate Ireland Adaptation Network (CIAN). The adaptive plan, its implementation and the associated monitoring system (including signals) need to safeguard the effective implementation of the CRDP, which is a demanding endeavour. They should be carefully designed and further refined together with the city stakeholders in Cork City, as well as relevant regional and national entities.

4. Discussion

CRDAPP is a pragmatic and technical approach for decision analysis, aimed at better integrating AMD planning, over time. It is not meant as a comprehensive approach to CRDP planning. This limitation is a trade-off between completeness and attempting to make a concept like CRDP more tangible for decision makers. On the one hand, an analytical approach like CRDAPP risks reducing CRDP to a solvable problem or box-checking exercise, and reinforcing existing inequalities and paradigms. On the other hand, not breaking down elements of CRDP into manageable components or actions, makes it hard for decision makers to get started and delays action. Given the systemic changes needed for CRDP, no single approach or tool will be both comprehensive and actionable. Instead, we imagine a collection of theories, approaches and practices will be used together to enable CRDP. Further, transformational change is a social learning process that will involve trial and error, iterations and corrections, as well as tailoring to local contexts and needs. CRDAPP is a first attempt at one approach to support CRDP decision making.

Nevertheless, CRDAPP requires further theoretical and practical elaboration. Firstly, in this paper, we focus mainly on what measures and pathways could be possible and less on how to implement them. Implementation requires connecting with frameworks and methods from social and environmental justice, grounded political economy, and governance, including aspects related to institutional complexity, political agency, legitimacy, deliberation and power asymmetry. Further, barriers to institutional uptake and ways to overcome them will be important for success in practice. Work done by Butler et al., 2022; Filho et al., 2021; Kareem et al., 2020; Marks et al., 2022; Rodríguez and Carril, 2024; Stringer et al., 2022; Stroombergen and Lawrence, 2022; Termeer et al., 2024, could help strengthen these aspects. Decision making tools and frameworks such as Robust Decision Making or Adaptive Governance, could complement CRDAPP with the assessment of robust pathways and analysing governance complexity (Chaffin et al., 2014; Folke et al., 2005; Kwakkel et al., 2016; Marchau et al., 2019; Ostrom, 2014). Secondly, methods and tools for participatory planning and co-designing pathways together with stakeholders can complement the CRDAPP approach and ensure procedural justice, such as those that have been applied in various adaptation studies (e.g. Campos et al., 2016; Haasnoot et al., 2024; Haque et al., 2012). Similarly, methods that account for multi-actor decision making and institutional loop learning could complement the approach (e.g. Macharis et al., 2012; Williams and Brown, 2018). Further testing and development in other cities and application areas will mature the approach for a range of governance and socio-ecological contexts, and surface limits in its generalisability. Finally, monitoring is a central and often challenging part of adaptive pathways planning and it becomes more complex for CRDP. Monitoring for CRDP must bring together information about adaptation, mitigation, and sustainable development, as well as justice. Setting up and maintaining such a monitoring system will require new types of indicators to cover AMD and their interactions. Furthermore, the institutional arrangements within which monitoring systems operate require further research and attention, as do funding mechanisms to ensure implementation of adaptive plans (Lawrence et al., 2020).

The case study for Cork City is a qualitative and illustrative example focused on key planning and policy decisions. While it represents a real case, a real planning process will be more complex, with more measures and thresholds at play, and it will need to address institutional feasibility, unintended consequences, governance and socio-economic complexities. Decision makers will also likely look for more extensive and insightful assessments of AMD interactions, for instance, through quantification, capturing spatial synergies and conflicts, and providing more detail about portfolios of actions, such as "circular economy" (e.g. Kool et al., 2024).

Our experience applying CRDAPP to the simplified and qualitative case study in Cork, brings us to reflect on the applicability of the approach in real planning processes. Most obviously, considering AMD objectives, actions and interactions was complex, even for this limited application. Naturally, the level of complexity will increase when additional actions, political processes and stakeholders are involved. Notably, the time, capacity and effort demanded for CRDAPP was already high and will become higher in a real planning process and/or when some quantification is needed. The three levels of analysis (section 2), can be combined to rely on stakeholder and qualitative assessments where possible, draw on existing information, available data and simple models when needed, and quantify only where important or necessary. Climate services could support quantitative analyses, alongside stakeholder evaluations. One of the challenges is to weave together the outputs from qualitative and quantitative information and assessments effectively during the creation of CRDP and for monitoring systems. Finding ways to communicate and visualize the analyses and results will also be important for real planning processes, particularly with a range of stakeholders. CRDAPP outcomes like pivotal decisions are compelling and tangible, but results need to be clear and digestible for a tractable approach. Part of communication is also ensuring that CRDAPP is understood as feeding a larger, comprehensive CRDP approach and is not taken as a complete plan.

5. Conclusions

Climate adaptation, mitigation, and sustainable development are increasingly recognised as intertwined challenges, and integrated action is called for through climate resilient development pathways (Howarth and Robinson, 2024; Schipper et al., 2022). This paper presents a first attempt at providing a decision analysis approach for integrating CRDP objectives over time. Building on Dynamic Adaptive Pathways Planning (DAPP), the Climate Resilient Development Adaptive Pathways Planning (CRDAPP) approach incorporates mitigation and sustainable development, alongside adaptation. Like DAPP, the CRD addition focuses on creating alternative pathways that allow for flexibility under uncertainty. It also illuminates potential path dependencies under a range of future conditions and adds the interrelationships between the elements of AMD. This paper explores whether such a decision analysis approach can contribute to the development and evaluation of CRDP. In this paper, we describe the CRDAPP approach and share a first illustrative and qualitative case study of Cork City, in Ireland.

The primary contributions of CRDAPP in Cork City were: (1) making a systematic overview of measures for different policy objectives and assessing their interactions; (2) highlighting different thresholds and pivotal decisions that may create dependencies or conflicts and trade-offs over time; and (3) developing narrative strategies toward different envisioned futures for the city to help align a coherent set of measures into pathways. For decision makers, identifying pivotal decisions and potential lock-ins from near-term decisions is actionable information. Similarly, identifying where important interactions lie which require an integrated approach – and where not – can help focus planning efforts. Using visions for the city and demonstrating how individual actions taken over time contribute to or interfere with achieving different visions, can also help engage stakeholders in transformational change.

Our first case study in Cork City also sheds light on the complexity of CRDP in practice. Even a simplified and qualitative assessment that was limited to decision analysis, burgeoned in difficulty – both in applying CRDAPP and in communicating the approach and its results. Additional developments and applications are needed to further elaborate CRDAPP, and it must be complemented and enriched by frameworks and approaches from fields like governance, justice and participatory planning. However, in its limited scope as a decision analysis approach, CRDAPP shows the immense challenges of integrating adaptation, mitigation, and sustainable development for making planning decisions.

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CRediT authorship contribution statement

Gaby S. Langendijk: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sadie McEvoy:** Writing – review & editing, Methodology, Conceptualization. **Denise McCullagh:** Writing – review & editing. **Marjolijn Haasnoot:** Writing – review & editing, Methodology, Conceptualization.

Declaration of competing interest

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

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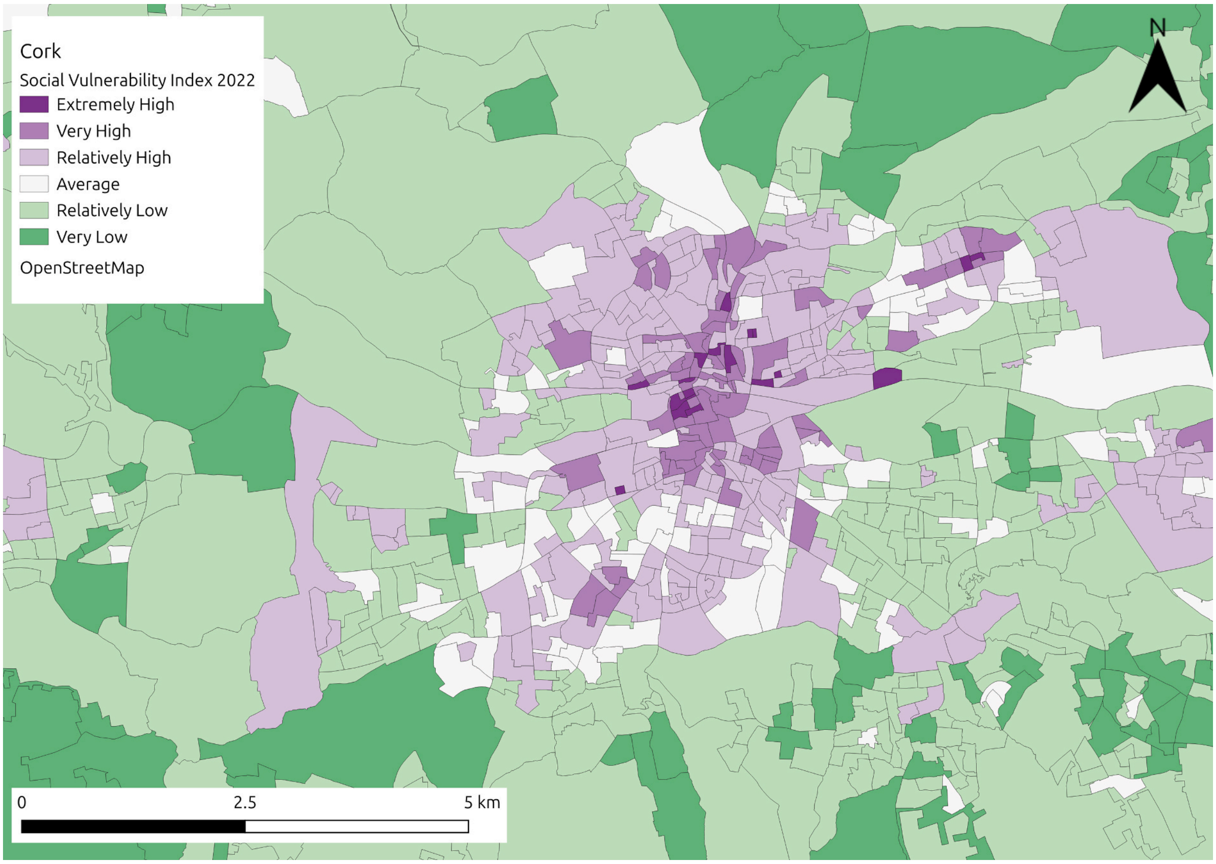
Appendix A. . AMD interaction types and associated definitions

Feasibility and effectiveness of AMD measures	
Synergy	A synergy refers to a situation when *simultaneous implementation* of two or more measures produces benefits greater than the sum of individual measures (Sharifi, 2020; Grafakos et al., 2019).
Conflict	Conflicts refer to situations when two measures are incompatible and their simultaneous implementation is not possible (Landauer et al., 2015).
Side-effects of AMD measures	
Co-benefit	A positive effect that a policy or measure aimed at one objective has on another objective, thereby increasing the total benefit to society or the environment. Co-benefits are also referred to as ancillary benefits (IPCC AR6).
Trade-off	A competition between different objectives within a decision situation, where pursuing one objective will diminish achievement of other objective(s). A trade-off exists when a policy or measure aimed at one objective (e.g., reducing greenhouse gas emissions) reduces outcomes for other objective(s) (e.g., biodiversity conservation, energy security) due to adverse side effects, thereby potentially reducing the net benefit to society or the environment (IPCC AR6).
Lock-in	A situation in which the future development of a system, including infrastructure, technologies, investments, institutions and behavioural norms, is determined or constrained ('locked in') by historical developments (IPCC AR6).

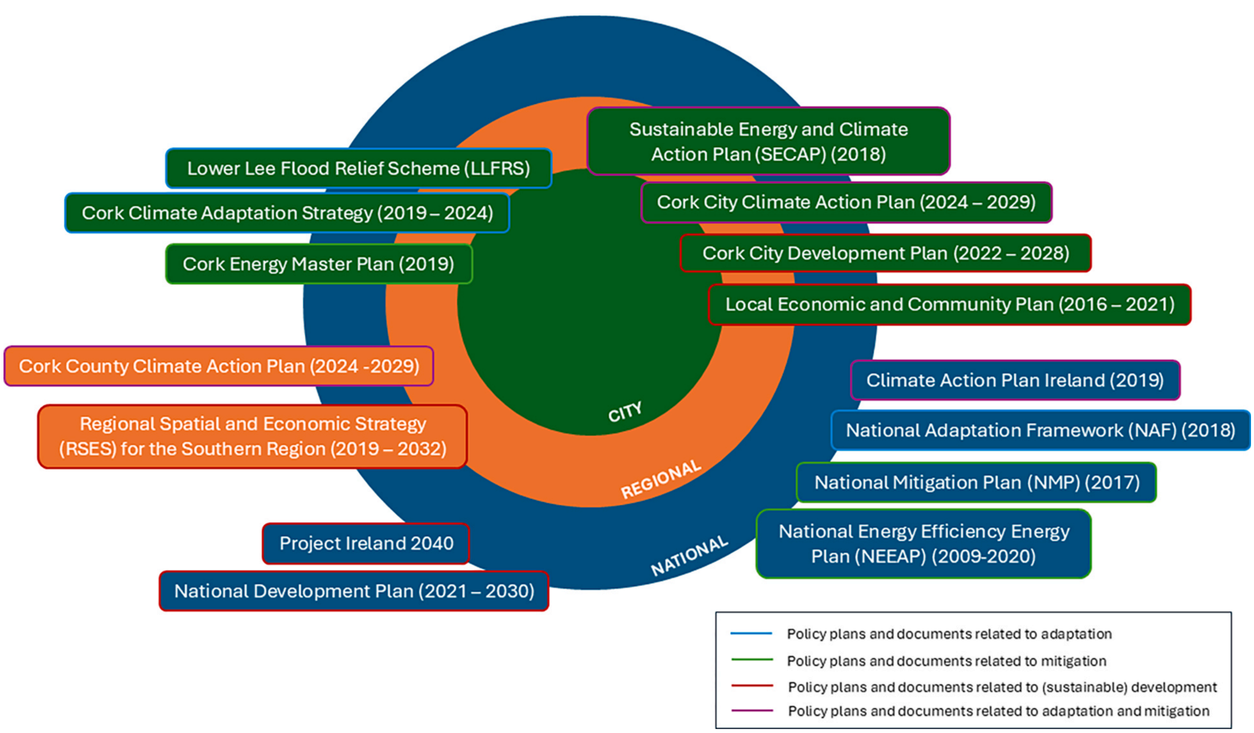
Appendix B

Social vulnerability index for Cork City, based on census data of 2022. The method for calculating the index is explained in Fitton, O'Dwyer and Maher (2022) and McCullagh et al. (2025).



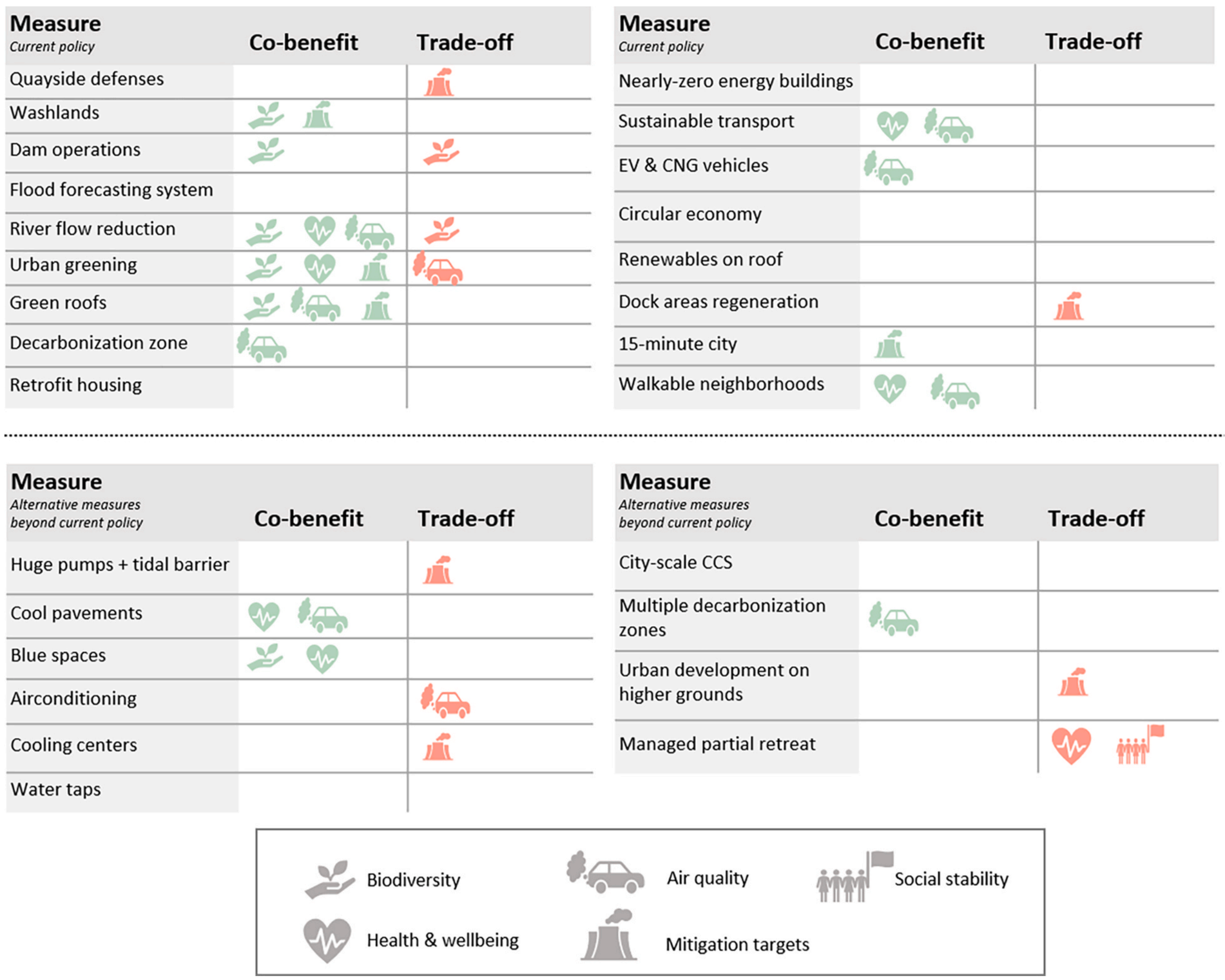
Appendix C

Overview of policy plans and documents related to adaptation, mitigation and (sustainable) development, on the Cork city level (green), regional level (orange), and national level (blue).



Appendix D

Side-effects of the measures on other objectives, so-called co-benefits and trade-offs, here: biodiversity, health & wellbeing, air quality, mitigation targets, social stability, for the measures from the currently existing policy (top) and alternative future measures (bottom).



Appendix E

Narratives describing the climate resilient development pathways for the three CRD strategies for Cork City.

1. **“Protect, green & circular, compact”**
In the short-term current policy will be largely followed: LLFRS will be implemented and the mitigation measures within the CAP 2024–2029 will be implemented, as well as the development plans for the dock areas regeneration will be executed. Under climate change with rising sea levels and increased heavy precipitation in fall/winter, only some of the LLFRS measureswill remain effective/viable (such as the EWS, river regulation), other measures will be useful but no longer offering sufficient protection to flooding in the mid-term – particularly not for the old town and the newly constructed districts in the dock areas. Additional measures are needed. As this CRD strategy envisions full protection and aims at green solutions, the washlands upstream will be enlarged and higher floodwalls will be constructed to protect Cork city from river and tidal flooding. In the long-term a tidal barrier is needed to offer full protection from tidal flooding due to increasing SLR. Heat is becoming an increasingly pressing issue in Cork in the short to long-term. Green spaces and green roofs are currently planned and will be created to relieve the population from heat stress in summer periods. In the mid-term additional measures will be needed, such as cool pavements and blue spaces. Thereafter cooling centers will be built to accommodate vulnerable population during extreme heat periods, and water taps will be installed throughout the city. Mitigation targets will be partly reached by 2030, in line with the current mitigation measures. Thereafter further mitigation measures will be needed to reach the next targets in the mid-term to ensure a

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durable carbon neutral city and to reduce further emissions due to e.g. the influx of people. Further mitigation is mainly through continuing with sustainable transport (walking, cycling, bus/tram) and a circular economy, as well as upscaling the decarbonatization zones, that are walkable with green spaces. The new population influx will be accommodated in a compact city approach, with sufficient housing by 2040. It includes a smaller sub-neighborhood planning to ensure a 15-minutes city (having key services within reach) and making the city walkable.

2. **"Partial protect, tech-fix, sprawl"**

In the short-term current policy will be largely followed: LLFRS will be implemented and the mitigation measures within the CAP 2024–2029 will be implemented. The development plans for the dock areas regeneration will be executed, nevertheless with elevated housing and carefully flood-proofing the area and buildings. Under climate change with rising sea levels and increased heavy precipitation in fall/winter, only some of the LLFRS measures will remain effective/viable (such as the EWS, river regulation), other measures will be useful but no longer offering sufficient protection to flooding in the mid-term – particularly not for the old town and the newly constructed district in the Dock area. Additional measures are needed. As this CRD strategy envisions partial protection through using infrastructure (higher quayside defenses) and strengthening existing tech-solutions, the excess water coming in from other side-streams will be pumped and managed better. In the long-term a tidal barrier + large pumps are needed to offer further protection from tidal flooding due to increasing SLR. Nevertheless, Cork city will be flooding from time to time. Heat is becoming an increasingly pressing issue in Cork city in the short to long-term. Tech solutions will be stimulated, starting with air conditioning in housing (e.g. through subsidy scheme) and public buildings/areas to relieve the population from heat stress in summer periods. In the mid-term additional measures will be needed and cooling centers will be built to accommodate vulnerable population during extreme heat periods, and water taps will be installed throughout the city. Mitigation targets will be partly reached by 2030, in line with the current planned mitigation measures and targets. Particularly there will be a focus on installing renewables on roofs and stimulating EV/CNG vehicles. Thereafter further mitigation measures will be needed to reach the next targets in the mid-term to ensure durable net-zero emissions and reduce further emissions due to the influx of people. This will be mainly done through the newly available technology: carbon capture and storage at the city scale. The new population influx will be accommodated in regenerated dock areas in the short-term and in city enlarged development areas on the city edges in the mid-term, with sufficient housing by 2040. The Dock areas will be elevated (primarily housing/businesses) and the areas will be designed in a flood-proof manner. It includes making the city walkable.

3. **"Accommodate, green & circular, sprawl"**

In the short-term current policy will be followed: LLFRS will be implemented and the mitigation measures within the CAP 2024–2029 will be implemented. Due to considerations w.r.t increased flooding now and in the future, the development plans for the dock area regeneration will be omitted, instead more urban development areas will be selected on higher grounds. Under climate change with rising sea levels and increased heavy precipitation in fall/winter, Cork city is increasingly subject to flooding, and a partial managed retreat strategy will be followed to ensure a livable Cork city in the long-term and to protect population from flooding. Only some of the LLFRS measures will remain effective, in the mid-term the excess water coming in from other side-streams will be pumped and managed better, and upstream washlands will be enlarged. In the long-term Cork will be partly relocated to higher grounds and no major flood protection measures will be taken in the long-term. Heat is becoming an increasingly pressing issue in Cork in the short to long-term. Green spaces and green roofs are currently planned and will be created to relieve the population from heat stress in summer periods in the short-term. In the mid-term additional measures will be needed, such as cool pavements and blue spaces. Thereafter cooling centers will be built to accommodate vulnerable population during extreme heat periods, and water taps will be installed throughout the city. Mitigation targets will be partly reached by 2030, in line with the current mitigation measures. Thereafter further mitigation measures will be needed to reach the next targets in the mid-term to ensure a durable carbon neutral city and to reduce further emissions due to e.g. the influx of people. Further mitigation is mainly through continuing with sustainable transport (walking, cycling, bus/tram) and a circular economy, as well as upscaling decarbonatization zones, that are walkable with green spaces. The new population influx will be accommodated in enlarged development areas on the city edges in the short and mid-term, with sufficient housing by 2040. It includes making the city walkable. In the long run a plan for partial retreat will be created, leaving no one behind.

Data availability

No data was used for the research described in the article.

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