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ORIGINAL ARTICLE

Climate resilient development in vulnerable geographies

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Abstract
The Intergovernmental Panel on Climate Change highlights the urgent need to operationalise Climate Resilient Development Pathways (CRDP), adopting mitigation and adaptation measures to secure a safe climate, meet human needs under a changing climate and enable sustainable development. Analyses have not yet compared different vulnerable geographies to understand similarities and differences in the constraints and opportunities in operationalising CRDP. Using conventional narrative literature review, this paper assesses CRDP across some of the world's most vulnerable geographies: highlands (mountains), drylands and islands. It asks: (1) how are climate impacts experienced across highlands, drylands and islands and (2) what types of adaptation and mitigation are being employed across these vulnerable geographies? Key steps are discussed in moving towards CRDP via multiple enabling conditions. Findings show shared impacts across geographies include impacts on ecosystems, fisheries, agriculture and water systems, livelihood failure, food insecurity, and degradation of human health, inequality, losses to economic sectors, human migration and conflict, and cascading transboundary impacts. Adaptation and mitigation actions tend to focus on promoting nature-based approaches, livelihood diversification and economic development, harnessing mixed knowledges and policy and institutional measures. Actions with potential to accelerate transitions towards CRDP should focus on the specific arenas of engagement shaping the underlying vulnerability context of each geography, including the socio-cultural context, politics, governance and institutions, the economic and financial systems, knowledge availability, and technological capabilities.

Keywords Climate adaptation and mitigation · Triple wins · United Nations Framework Convention on Climate Change (UNFCCC) · Pathways · Resilience

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1 Introduction

Connections between climate change and socio-economic development are widely acknowledged and have been conceptualised in a variety of ways (Nuna 2017). Recognising that development must not increase emissions nor reduce capacities to mitigate and adapt (Favretto et al. 2018; Thornton and Comberti 2017), approaches that conceptualise the interlinkages needed when exploring trade-offs and synergies in linking mitigation, adaptation, and development, include triple wins (Suckall et al. 2015), low carbon development (Yuan et al. 2011) and climate-compatible development (Nunan 2017). The prioritisation of combined adaptation and mitigation actions is also supported by activist social movements globally (de Moor 2022). In international climate policy circles, the concept of Climate Resilient Development Pathways (CRDP) was introduced in the IPCC's Fifth Assessment (AR5) (Denton 2014) and gained traction following the Paris Agreement, which emphasises increasing the ability to adapt to adverse climate impacts, fostering climate resilience, and promoting low greenhouse gas emissions development without threatening food production (UNFCCC 2015). The Sustainable Development Goals (SDGs) further reinforce the CRDP framework (Minx 2017) while the IPCC Working Group II's Sixth Assessment (AR6) dedicated a whole chapter to pursuing CRDP, calling for mitigation and adaptation measures to secure a safe climate, meet human needs and enable sustainable development (Schipper 2022).

AR6 highlights the need to operationalise CRDP to promote multiple system transitions, encompassing social, economic, technological, institutional, and governance aspects of development (Schipper 2022). However, practical examples of CRDP are limited, with notable exceptions such as its adoption in local-level urban planning in Cape Town (Simpson et al. 2021). Understanding how the concept can operate in highly vulnerable areas, where development is most urgent and climate change impacts are greatest, remains a critical knowledge gap addressed in this paper.

Three vulnerable geographies in the context of climate change and development are highlands (mountains), drylands and islands (IPCC 2022). In recognition of their vulnerability, these systems were each allocated a dedicated chapter in the IPCC AR6 WG2 Report. Their livelihood systems are vulnerable to climate change impacts, with shared characteristics such as geographical remoteness, high levels of poverty (particularly in the developing world), limited diversification in production and exports, heavy dependence on external trade, and high vulnerability to economic shocks. Small islands for example, depend heavily on marine and coastal biodiversity to sustain livelihoods, making efforts to reduce ecosystem damage and biodiversity loss due to climate change vital for the well-being of their populations (Vogiatzakis et al. 2016). Livelihoods across highlands, drylands, and islands often rely on natural ecosystems, which are under pressure from rapid population growth. These geographies can also suffer from unstable governance, low institutional capacities, high unemployment, and a lack of infrastructural investments (Stringer 2021). Sub-Saharan African drylands, for instance, face high levels of poverty, land degradation and socio-economic marginalisation, combined with limited capacities to address climate change (Bawden 2018). Similar challenges are present in fragile mountain areas and highlands, which are hotspots of climate-related losses, shaped by heterogeneous land use resulting from the abandonment of unfavourable agricultural land, alongside intensification in the most favourable areas (Adler 2022; Lavorel et al. 2023).

While some climate impacts, such as livelihood failures and economic losses, are shared across these geographies, others are specific to their contextual characteristics. For example, ecosystem service losses may result from drought-induced avalanches in highlands, increased sand and dust storms in drylands, and submergence and flooding due to sea level rise on islands (IPCC 2022). Nevertheless, little is known about how these impacts differentiate across vulnerable geographies and how they can be addressed to transition towards CRDP. This paper targets this gap by assessing adaptation and mitigation across highlands, drylands and islands with a view to identifying key steps in moving towards CRDP. It investigates: (1) how are climate impacts experienced across highlands, drylands and islands and, and (2) what types of adaptation and mitigation responses are being employed across these vulnerable geographies? Findings emphasise the context-appropriate enabling conditions across different arenas of engagement in each of these applied settings. We hypothesise that the nature of the underlying vulnerabilities is more important than the geographical characteristics of highlands, drylands, and islands in defining how CRDP can be pursued and the enabling conditions that require the most emphasis.

2 Materials and methods

2.1 Conceptualising climate resilient development pathways

Climate resilient development, as defined by the IPCC, involves "implementing greenhouse gas mitigation and adaptation measures to support sustainable development for all" (IPCC 2022:2917). CRDP are "trajectories that strengthen sustainable development and efforts to eradicate poverty and reduce inequalities while promoting fair and cross-scalar adaptation to and resilience in a changing climate" (IPCC 2022:2917). AR6 operationalises CRDP through the pursuit of policies and practices that integrate mitigation, adaptation, and sustainable development over time (Schipper 2022). For instance,Skrimizea and Parra 2020 illustrate how pathways approaches in water management and governance on Greek tourist islands can transform political and socio-economic structures and shift norms and values, reconfiguring institutions and regulations. Similarly, AR6 recognises numerous potential pathways for success. However, the challenge lies in identifying and operationalising those pathways that address current climate variability and change while ensuring future planetary health and human well-being. Effective CRDP involves actions and social choices under multiple governance dimensions, including politics, institutions, and practices shaped by diverse values and worldviews. Outcomes and processes along each pathway manifest in various arenas of engagement – community, socio-cultural, political, ecological, knowledge-technology, and economic-financial – enabled by actions focusing on ecosystem health, knowledge diversity, equity, justice, and inclusion (Schipper 2022). CRDP outcomes involve system transitions across energy, land and ecosystems, urban and infrastructure, and industrial systems, catalysing wider societal transformations. These transitions often occur at different temporal and spatial scales and necessitate extensive stakeholder networks to engage social groups, sectors, and disciplines across scales, maximising opportunities for transformative CRDP (Taylor et al. 2023).

2.2 Defining vulnerable geographical regions: highlands, drylands and islands as the contexts in which to investigate CRDP

Highlands are distinguished by their altitude and elevation (Fig. 1a), drylands by their climate (Fig. 1b), and islands by their maritime surroundings (Fig. 1c).

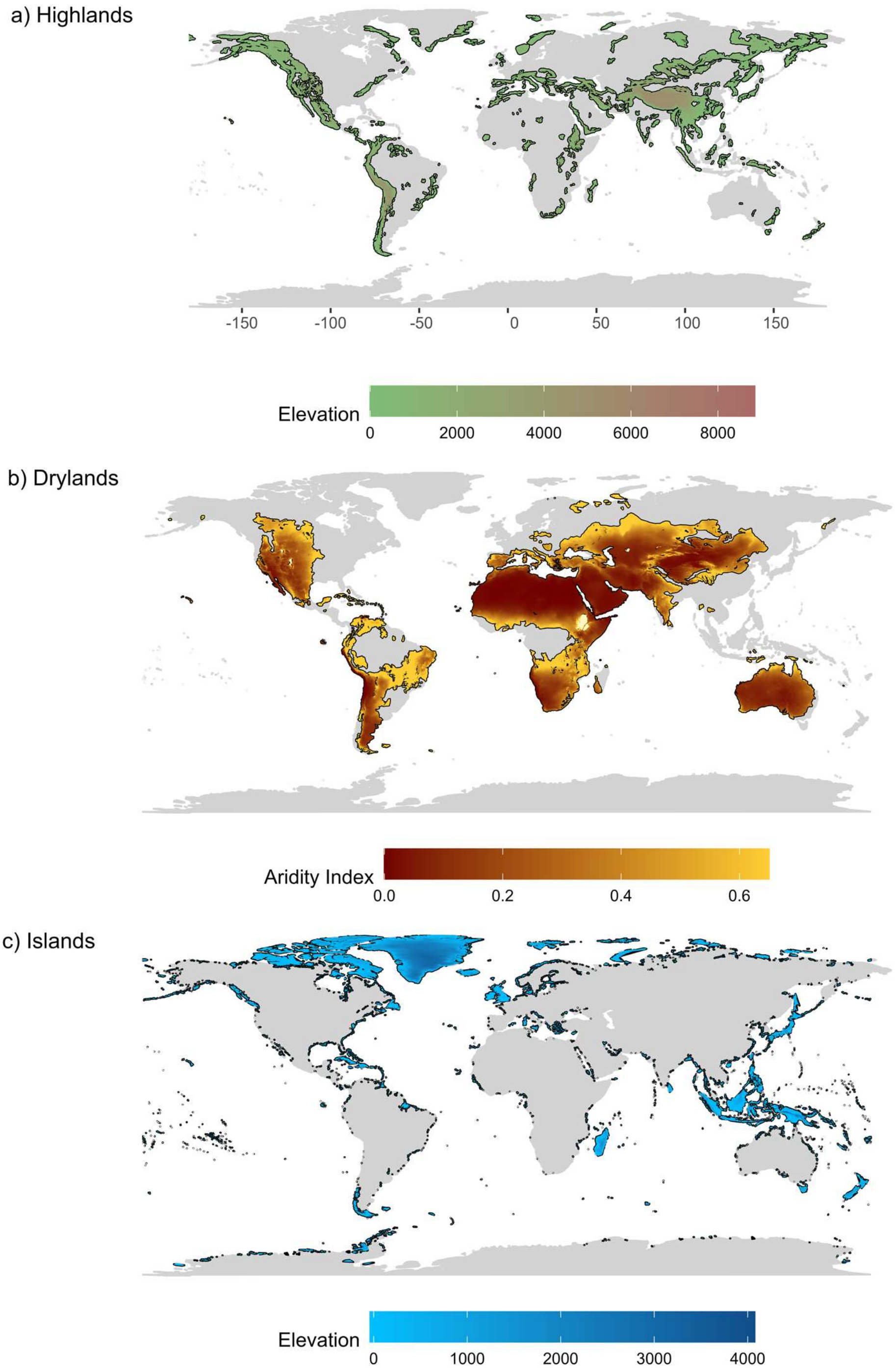

Fig. 1 Maps showing (**a**) highland areas globally, adapted from (Körner et al. 2017); (**b**) global drylands, adapted from (Sorensen 2007) and UNEP-WCMC 2007; and (**c**) the world's islands, adapted from (Sayre 2019). Drawn by Juan Antonio Hernández-Agüero

All three geographies have mixed definitions. Their categories can be, but are not always, distinct (Fig. 2).

We define highlands as upland areas characterised by higher elevation compared with their surroundings (with mountains being > 300 m.a.s.l.), often with rugged terrain and glaciers, snow cover or permafrost (Adler 2022; Huggel et al. 2015). The global mountainous area accounts for c.32 million km^2 (c.23.5% of the global land surface (Fig. 1a), hosting 1.28 billion people in 2015 (Adler 2022). Drylands are hyper-arid (Aridity Index (AI) < 0.05), arid ($0.05 \leq AI < 0.2$), semiarid ($0.2 \leq AI < 0.5$) and dry sub-humid ($0.5 \leq AI < 0.65$) areas covering c.45–47% of the land worldwide (Fig. 1b). Drylands host unique biodiversity and c.3 billion people Koutroulis et al. 2019; Mirzabaev 2019). No single definition of islands exists. AR6 covers independent island states, archipelagic states, and non-sovereign island states and territories dependent on continental states located within the tropics of the southern, northern, and western Pacific Ocean, the central, eastern and western Indian Ocean, the Caribbean Sea, the eastern Atlantic off the coast of West Africa, and in the temperate Mediterranean Sea (Mycoo 2022). Small Island Developing States (SIDS), a distinct group of 39 small and remote island developing states, face the highest risks from projected climate changes. AR6 gives no indication of what area constitutes a "small" island. Here, we define islands as land surrounded by water and smaller than Greenland (Fig. 1c). Islands host unique biodiversity and cultures with a maritime environment that often attracts tourism but is vulnerable to climate change. Given their often-insular nature, they have highly coupled terrestrial and marine ecosystems, exposing them to direct impacts from natural and anthropogenic changes (Mycoo 2022).

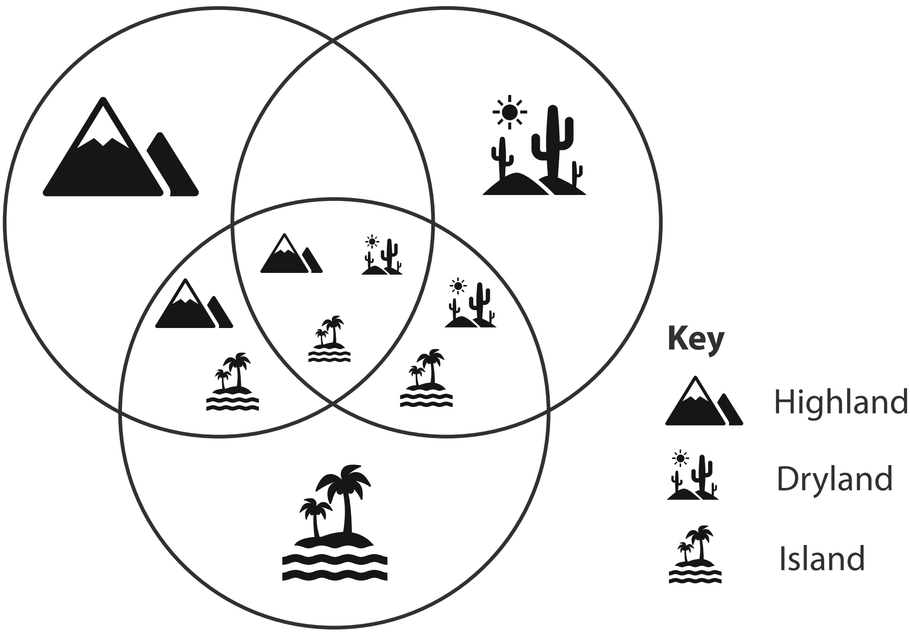

Fig. 2 Venn diagram showing possible combinations of highland, dryland and island categories

2.3 Research design and methodology

We first developed a framework (Fig. 3) focused on current and future climate change impacts, CRDP enabling conditions, and transitions towards CRDP, building from AR6. The framework allows exploration of CRDP across a wide range of contexts, and is therefore suitable to apply to the vulnerable geographies addressed in this paper.

An exploratory review of Schipper (2022) and literature on CRDP enabled question-setting, informing development of Fig. 3. In-depth screening of AR6's chapters and cross-chapter papers on our selected vulnerable geographies and CRDP was then undertaken, expanded with academic literature following the review approach outlined by Levy and Ellis (2006). Using a flexible and non-systematic approach, literature was searched drawing on the key references from AR6, then extracting additional references in Scopus and ScienceDirect guided by search terms 'climate AND resilien* AND development' and 'adaptation AND mitigation AND development'. Similar concepts such as climate compatible development and triple wins were not considered, so we could build directly on the AR6. Despite including CRDP's dimensions in the search terms, our starting point was adaptation, in line with Working Group II, allowing us to expand to consider the mitigation and development implications of identified adaptations. Given the breadth of literature on climate change, searches were temporally restricted to papers from 2015 up to November 2023, allowing contextualisation of development according to the adoption of the Sustainable Development Goals (SDGs) in 2015. As detailed in Table 2, a total of 36,654 papers were initially identified. The non-systematic, narrative review approach informed by Levy and Ellis (2006) allowed relevant information to be extracted from the wide range of identified papers, without setting strict inclusion and exclusion criteria. Evidence needed to address the research questions was iteratively extracted from individual sources, and summarised and categorised into a matrix comprising the key components of Fig. 3 (i.e. key climate change impacts, and adaptation and mitigation responses). A total of 109 sources were reviewed, allowing us to satisfactorily address the conceptual framework's components, particularly evaluating the mitigation and development implications of adaptations across different arenas of engagement. Tables 3 and 4 provide an

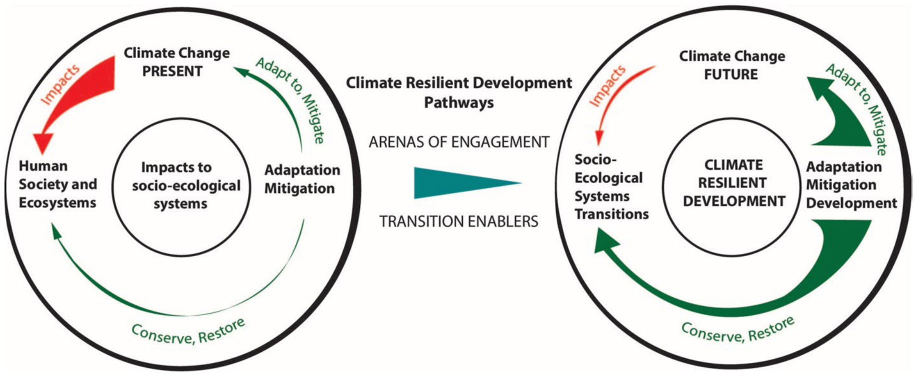

Fig. 3 Conceptual framework to operationalise a shift from present climate change impacts and adaptation and mitigation responses toward future climate resilient development pathways (adapted from Schipper (2022)). Red arrows represent climate impacts (thicker/stronger in the present, slimmer/smaller in the future). Green arrows represent the benefits of adaptation and mitigation, in terms of conservation, restoration, provision of ecosystem services and human wellbeing and livelihood improvement (smaller in the present, stronger in the future).

overview of the key literature reviewed to address each of the key themes: i.e. climate change impacts identified across geographies, and the related adaptation and mitigation responses. In line with the steps described by Levy and Ellis (2006), analysis of the literature using the narrative review method allowed qualitative interpretation of the multiple enabling conditions required to move towards CRDP across highlands, drylands and islands (Sylvester et al. 2013) (Fig. 4). Locations with different socio-economic development (low to high) and political contexts were identified drawing on Fig. 1, which led us to illustrative examples from Italy (highland/dryland/islands), Nigeria (dryland) and Papua New Guinea (highland/island) to show how adaptations interplay with the arenas of engagement (see Table 1 in Sect. 3).

Limitations of our approach include a lack of academic literature using CRDP language, which limited the breadth of references identified, despite having initially identified over 36,000 papers that cover multiple dimensions of CRDP. We acknowledge that the analysis presented is not comprehensive, as it only examines a limited number of scientific papers in a non-systematic manner, which only capture a focused range of on the ground realities. By including the individual CRDP components in the search terms, and using a flexible approach, we nevertheless maximised inclusion of relevant publications, which would have otherwise been constrained in a systematic approach. Exclusion of grey literature and that in other languages besides English may miss examples of CRDP in practice. However, grey literature was deliberately excluded to allow us to build on scientific evidence. Starting with adaptation options implies a secondary focus on mitigation. However, such prioritisation reflects the conceptual lens of AR6's WGII from which we build and generates

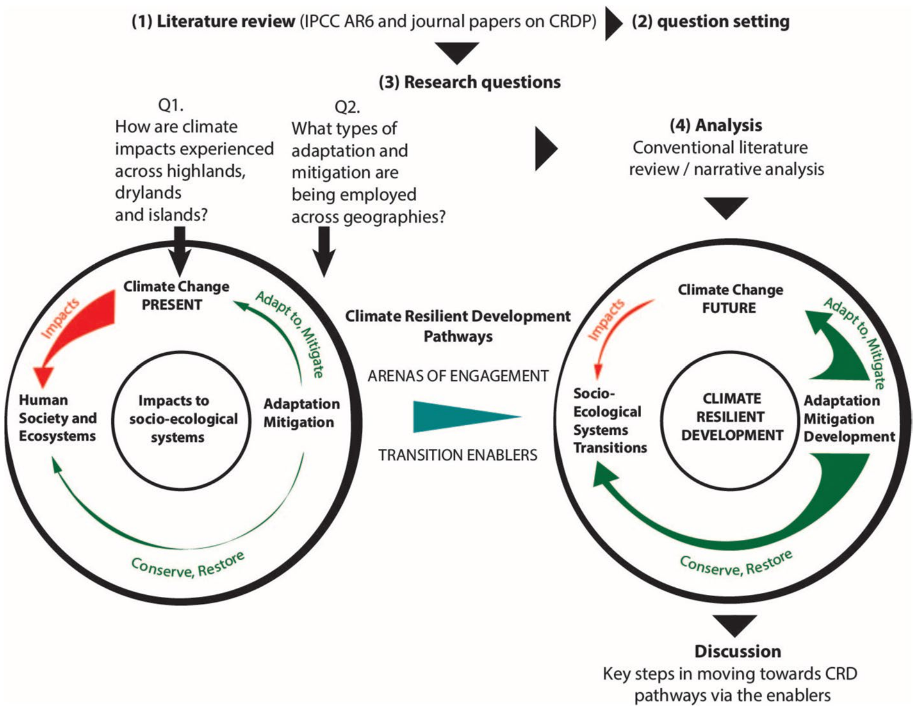

Fig. 4 Visual flow of the data collection and analysis approach

meaningful considerations of what adaptation action means for both mitigation and development, therefore tackling all CRDP dimensions.

3 Results

3.1 How are climate impacts experienced across highlands, drylands and islands?

Climate impacts on vulnerable socio-ecological systems are driven by various factors, including rising temperatures and altered rainfall patterns, resulting in increased droughts, pests, and extreme events such as storms and heatwaves. These drivers have both direct and indirect effects on seven key types of impacts identified across highlands, drylands and islands, as detailed below with illustrative examples from referenced studies.

3.1.1 Impacts on ecosystems and biodiversity

Impacts on ecosystems and biodiversity, encompassing both economic and non-economic harms from observed climate change impacts, are significant across vulnerable geographies (Mechler 2018). In highlands, these impacts manifest through floods, debris flows, landslides, and avalanches, which elevate extinction risks for rare, endemic species, especially those unable to migrate to higher elevations or cooler locations. Manes et al. (2021) report that 84% of global endemic species in mountain regions face high extinction risks. In drylands, ecosystem and biodiversity health are threatened by severe warming and aridity, characterised by sparse vegetation cover, low soil moisture, increased evapotranspiration, and higher drought frequency, severity, and duration. Projections indicate a 23% increase in global dryland area by 2100 compared to 1961–1990 (Huang et al. 2016). However, the extent of projected dryland expansion varies with definitions, as meteorological and vegetation-based definitions offer differing estimates (Stringer et al. 2017). Aridity index-based projections show contrasting evidence, with some drylands expected to contract while others expand (He et al. 2019; Li et al. 2021). These changes are expected to significantly alter the global carbon cycle and nutrient cycling, promote woody encroachment, increase tree loss, reduce perennial vegetation cover due to invasive plants and wildfire, and diminish ecosystem services (Stringer et al. 2017). Increased aridity in some drylands will also reduce vegetative cover and rangeland productivity, contributing to land degradation and more frequent sand and dust storms. Similarly, islands will experience losses of marine and coastal ecosystems. Sea level rise will exacerbate submergence, coastal flooding, and erosion of low-coastal and reef islands. Temperature rise and ocean acidification will lead to severe coral bleaching, potentially losing 70–90% of reef-building corals (Salmon et al. 2019), with cascading impacts on broader island ecosystems. Island terrestrial ecosystems and biodiversity face high extinction risks for endemic species. In recent decades, tropical islands experienced increasing shoreline retreat and beach loss due to tropical cyclones and human disturbances. For example, on the remote Pacific island of Tubuai in French Polynesia, 57% of the shoreline experienced beach area retreat between 1982 and 2014 (ibid.).

3.1.2 Impacts on fisheries and agriculture

In highlands, climate change adversely affects agriculture through increased exposure to droughts and floods, changes in seasonal onset, and shifts in the timing and availability of water, all of which exacerbate pest issues and decrease pollinator diversity. These changes collectively reduce livestock productivity, food production, dietary diversity, and the nutritional value of crops (Adler et al. 2022). Early flowering and shorter vegetative phases negatively affect medicinal and aromatic plants. A household survey in the Koshi River Basin, Nepal, indicated that in 2011–2012, approximately 40% of the 2,310 farmers engaged in the study reported a decline in staple crop production attributed to climate change (Hussain et al. 2018). These changes often have downstream impacts at lower altitudes. In drylands, recurrent droughts combined with wind erosion lead to reduced crop yields, land abandonment, and agricultural fields being overtaken by sand and invasive plants, which, in turn, reduce livestock yields and increase livestock injury or death due to sand and dust storms (Tsymbarovich et al. 2020). Islands face a reduction in crop varieties and are particularly vulnerable to future declines in fishery productivity, due to the decline or extinction of reef-associated species from coral bleaching or cyclone damage, alongside changes in fish breeding behaviour and migration. A global study on thermal stress and recovery trajectories of fish communities under climate change and coral bleaching shows that ocean yields will decrease as fish communities historically associated with coral reefs fail to re-establish (Robinson et al. 2020).

3.1.3 Impacts on water systems

Highland water cycles experiencing glacier shrinkage and snow cover changes, are increasingly leading to variations in the amount and timing of glacier melt and snowmelt stream discharge, causing significant knock-on effects. Almost 70% of lowland irrigation systems depend on glacier melt and snowmelt from highlands, leading to erratic water supplies and increased food insecurity for lowland populations. By the mid-twenty-first century, this is estimated to affect c.1.5 billion people (24% of the world's lowland population), particularly in regions heavily reliant on mountainous water sources, such as Central and South Asia, tropical and subtropical western South America, and southwestern North America (Viviroli et al. 2020). Changes in rainfall, river flow regimes, and landslides will limit hydropower production and use in highlands. Similarly, drylands will experience water loss and decreased water quantity for irrigation, especially as aridity increases, alongside rising contamination of surface water bodies. In Morocco, a study estimated that between 2031 and 2050, climate change will decrease the annual water supply in the northern part of the country by 17–28% (Choukri 2020). Increasing aridity will also reduce fresh groundwater volume in island systems, with small islands (particularly dryland islands) being most severely affected due to low rainfall and high water demands for irrigated agriculture and tourism. Freshwater stress is expected to intensify for most small island developing states, particularly in the Caribbean and eastern Atlantic, under 1.5 and 2 °C warming scenarios (Karnauskas et al. 2018).

3.1.4 Livelihood failure, food insecurity, degradation of human health and inequality

Increasing vulnerability and livelihood insecurity due to climate change, along with worsening of human health, loss of cultural values, and rising inequality, are commonly reported across all three vulnerable geographies. Water insecurity heightens the potential for conflict over water resources in highlands, especially in seasonally dry regions. An analysis of climate change impacts on glaciers in the Peruvian Andes reports cascading livelihood effects, particularly affecting the downstream economies due to diminishing water availability (Motschmann 2020). A survey of farmers' perceptions in the Western Himalaya, Pakistan, highlights increasing physical injuries (from floods or landslides) and fatalities (from vector-borne diseases such as malaria or dengue fever), particularly at higher elevations under rising temperatures (Hussain 2019). Climate change also affects psychological wellbeing across all geographies, leading to mental health issues such as climate anxiety and ecological grief, as well as extreme weather events having impacts on social relations (Clayton 2020). In drylands, human health and food security are compromised by increasing water scarcity and aridity, with sand and dust storms exacerbating mental health issues alongside respiratory, cardiovascular and infectious diseases, as demonstrated in Iranian drylands (Goudarzi 2017). Undernutrition risks are especially severe for vulnerable populations, particularly children, who may suffer lifelong consequences such as impaired growth and cognitive ability (Myers 2017). Women and girls in drylands and highlands bear the most severe implications of climate change, spending more time collecting water and fuelwood, which reduces their time for education and income-generating activities, thereby exacerbating gender inequalities. Degradation of terrestrial and marine ecosystems increases climate vulnerability in small islands, leading to economic deprivation and the loss of cultural resources and heritage, with similar health risks to those faced in drylands and highlands. Increased dependence on imported food, which can increase emissions, and malnutrition are projected to be significant issues in small island developing states (Hickey and Unwin 2020). Small, overcrowded atoll islands that heavily rely on rainwater harvesting, such as Tuvalu, are more vulnerable waterborne diseases (McCubbin et al. 2015), and recent storms in Vanuatu have contaminated drinking water sources. Low governance and coordination capacities, combined with the islands' remoteness, hamper recovery and rehabilitation efforts.

3.1.5 Impacts on economic sectors, tourism and recreation

Reduction of snowfall, along with changes in its timing and quantity, significantly affects highland winter tourism and recreation, while rockfalls may hamper access to summer climbing and hiking routes. Projections across the French Alps and Pyrenees estimate that by 2100, there will be no natural snow-reliable ski resorts (Spandre 2019). Increased aridity and declining water availability in some drylands will reduce agricultural and livestock yields, lowering the profitability of food production and disrupting the economic structures and cultural practices of affected communities. Research in Botswana's Kalahari shows that climate change reduces opportunities for hunting and gathering of wild products, as well as wildlife and plant diversity (Favretto et al. 2021). These climate changes have limited the benefits derived from tourism and community-based natural resource management, exacerbating poverty for rangeland users and increasing dependence on government support and drought relief programmes (ibid.). Small island economies, typically lacking diversity, are particularly vulnerable to global climate-driven shocks. Coastal tourism is highly exposed to cyclones, beach erosion, coral bleaching, and associated marine biodiversity losses. A study of climate change effects on the coastal environment around the Caribbean and Mid-Atlantic UK Overseas Territories suggests that future increases in tropical storms and hurricanes will cause greater damage to coastal resources due to strong winds, wave action, and torrential rain (Murray 2021). This has already been observed in Anguilla, which between 1995 and 2010 was hit by eight hurricanes, affecting tourism-dependent livelihoods, destroying critical infrastructure, damaging fisheries (i.e. fishing vessels and fish traps), and resulting in the closure of several hotels (ibid.).

3.1.6 Human migration, reduced habitability, displacement and conflict

Temporary or permanent displacement of populations is a significant climate change impact across vulnerable geographies. In highland regions, displacement is primarily driven by hazards such as floods, avalanches, and landslides. In drylands, the main factors are the lack of livelihood opportunities and food insecurity, often related to drought and climate variability. In islands and coastal areas, displacement is mainly driven by cyclones, salinisation, and land loss from erosion and sea level rise, all of which reduce habitability (Dasgupta et al. 2022). Across these vulnerable geographies, infrastructure is under considerable stress from growing urban populations and the combined influx of migrants, tourists, and retirees, exacerbating pressure on declining water services. A study of water security in high mountain cities in Bolivia estimates that while water demand is expected to increase by approximately 53% between 2011 and 2036, projected water supplies will decrease due to climate stressors and decreasing glacial meltwater (Kinouchi 2019). Reduced habitability and displacement, combined with declines in access to ecosystem services, exacerbate the economic and political marginalisation of vulnerable populations. This has negative effects on livelihoods and increases the potential for conflict, as shown in glaciated environments (French et al. 2015) and sub-Saharan Africa's drylands (Almer et al. 2017).

3.1.7 Compound, cascading and transboundary impacts

Highlands, drylands and islands function as complex systems where multiple climate impacts interact dynamically. These interactions can result in compound and cascading impacts that may occur locally or spread across sectors and socio-ecological systems (Pescaroli and Alexander 2018), including crossing national borders. Flood risks will increase due to the combined effects of future sea level rise, storm surges, and rainfall changes, while health and food insecurity risks will worsen with rising heat and drought. Consequently, higher food prices and reduced household incomes will exacerbate malnutrition and mortality risks (Schipper 2022). Transboundary impacts may arise from dynamics originating in one geography, continent or system and spreading to other geographies or systems. Large deep ocean waves generated by extreme events may inundate island settlements, infrastructure, and tourism facilities, and drive coastal erosion, as demonstrated by 2018 flooding along Fiji's coast caused by a wave from the Southern Ocean and Tasman Sea, driven by an extra-tropical cyclone (Wandres 2020). Transcontinental dust cloud movements from Saharan drylands worsen human health issues such as asthma, cardiovascular morbidity, and pulmonary diseases in distant island regions like the Caribbean and Mediterranean (Goudie 2020). The localised, climate change-induced spread of invasive alien species poses significant threats to ecosystem and biodiversity health worldwide, particularly on islands (Russell et al. 2017). Additionally, the spread of climate change-driven pests and diseases in one geography or system contributes to the emergence of serious human diseases such as Dengue, Chikungunya and Zika, and plant diseases like Black Sigatoka, a major threat to banana plants spreading across island systems in Asia, Latin America and the Caribbean (Bebber 2019). These effects and interactions exhibit substantial complexity (see detailed literature covering how climate impacts can cascade across and within regions, systems and geographies (Zscheischler et al. 2018; Simpson et al. 2023).

3.2 What types of adaptation and mitigation are being employed in vulnerable geographies?

The adaptation and mitigation responses across highlands, drylands and islands have been grouped into six categories, as detailed below with examples.

3.2.1 Nature-based, land-based and ecosystem-based measures and approaches

Nature and land-based solutions commonly adopted across highlands, drylands, and islands to address climate change impacts and foster CRDP include land restoration and rehabilitation through afforestation, agroforestry, climate-smart agriculture, and restoration of mangroves and coral reefs in island geographies (Schipper 2022). A study of the impacts of agroforestry on mountain ecosystems indicates it promotes erosion control and ecosystem restoration (enabling both adaptation and mitigation), enhances local farmers' livelihoods by diversifying agricultural crops and livestock (adaptation and development), and boosts carbon sequestration by improving nutrient cycling and expanding tree cover (mitigation) (Dar 2023). Similar benefits are observed in drylands, as demonstrated by an agroforestry project in Malawi (2009–2014), which enhanced yields, agricultural income, and food security (development), while reducing deforestation and avoiding agricultural encroachment (mitigation) (Amadu et al. 2020). In these examples, capacity building for local land users on agroforestry techniques and benefits was crucial for adoption. Ecosystem-based adaptation measures or nature-based solutions can improve water quality, groundwater recharge and storage capacity. These measures sustain adaptation by increasing the availability, usability, and resilience of water resources, which are key for meeting basic development needs, and enable mitigation by increasing carbon uptake as water bodies can act as carbon sinks (Skwierawski 2022). A global systematic review of adaptation responses in major glaciated mountain regions indicates that restoring buffer zones and floodplains, and implementing integrated catchment management, effectively reduce flood and landslide risks, protecting key economic and development activities, and enhancing carbon sequestration by preventing erosion and supporting sedimentation in natural floodplains (Aggarwal 2021). In drylands, strategies focus on heterogeneous landscape restoration, such as tree regeneration to boost mitigation, as observed in rural villages in India (Kattumuri et al. 2017). Fire management and invasive species clearance are effective adaptation responses in tropical savannas and grassy woodlands (Buisson 2019). However, in island contexts like Hawaii, non-native plant invasions can increase aboveground carbon densities, and clearing these invasives may reduce carbon sequestration, despite improving other ecosystem services (Hughes 2017). Such trade-offs between adaptation and mitigation highlight conflicting implications for carbon stocks, biodiversity, and livelihoods, and must be carefully considered in moving towards CRDP. In Kalahari rangelands, herd mobility to avoid overgrazing near settlements, water points, and markets is a common adaptation. Appropriate grazing management allows grass regrowth, enhancing carbon sequestration (mitigation) and maximising meat production for subsistence (development) (Reed 2015). However, mobility is often unsupported by policies favouring sedentarisation, which can undermine pastoral communities' needs (Favretto et al. 2021). Strengthening justice and equity in land ownership and management is essential for enabling CRDP, as these policies typically benefit elites while marginalising local communities. In islands, ecosystem-based approaches focus on restoring coastal areas and marine ecosystems through reforestation, agroforestry, and beach nourishment. Several Pacific islands increasingly adopt reef-to-ridge ecosystem management and integrated watershed management to address system interconnections, secure downstream water, fight erosion, and conserve coral reefs (Förster 2019). These approaches enhance carbon storage by protecting upstream forests and incorporating soil conservation practices across ecosystems and agricultural lands, reducing degradation, while also improving downstream carbon sequestration. A case study of integrated landscape management in Latin America and the Caribbean shows that combining reef and mangrove conservation with sustainable land management (including agroforestry and reforestation) in upland areas of highland islands enhances carbon sequestration (mitigation), improves coastal ecosystems (adaptation and mitigation), and boosts local livelihoods (development) (Estrada-Carmona 2014).

3.2.2 Hard protection

Hard protection measures in highlands and islands primarily involve structural interventions such as constructing artificial barriers. Securing financing is a key enabler to cover the high installation and maintenance costs of these artificial measures, which are notably more expensive than natural barriers. For instance, the large-scale restoration of the Loess Plateau in China, which combined artificial and natural restoration methods, cost US$500 million, with US$300 million funded by the World Bank and the remainder provided by the government (Blaustein 2018). In highlands, sediment traps and outward sloping rain-fed terraces are commonly used to control soil erosion and enhance agricultural income and livelihood diversification. Chidi et al. (2022) found these measures highly effective in reducing soil erosion in Nepal's middle hills, where erosion rates remained consistent across different sites and rainfall conditions. Terracing also mitigates erosion and surface runoff, increases soil organic matter accumulation, and enhances carbon sequestration. Studies in China's highlands indicate that terraced fields have higher soil organic carbon contents than non-terraced lands, while manure application has been found to improve fertility and accelerate carbon aggregation (Chen et al. 2021). On islands, structural adaptations include building seawalls and breakwaters, and elevating buildings and roads to reduce exposure to sea level rise and flooding. Since the 1990s, these measures have been implemented in several Caribbean islands to reduce beach erosion and support reef restoration (Reguero 2018). Structural adaptations indirectly support mitigation by reducing inundation risks and preventing the erosion of carbon-rich coastal ecosystems. However, there are limitations to their effectiveness, as observed in Samoa, where large waves increased impacts under an adaptation project (Crichton 2018). In drylands, hard protection focuses on nature-based measures such live windbreaks, shelterbelts, and using crop residues and perennial plant species to trap sediments and form sandy mounds, as seen in Kuwait, to prevent sand encroachment and dust accumulation (Ahmed et al. 2016). Geotextiles also play a role in erosion control, as shown across degraded pasture soils in Brazil's Cerrado (Rodrigues Marques 2016). Nature-based protection often provides greater mitigation potential than 'grey' hard protection because tree planting, regreening, and natural barriers enhance carbon sequestration (Dar et al. 2023; Estrada-Carmona et al. 2014). Given the breadth of applicable nature-based solutions, capacity building and stakeholder engagement are essential for CRDP. These efforts enable diverse actors, including land and coastal users, the private sector, municipalities, and national government agencies, to identify and implement the most suitable solutions (Favretto et al. 2020).

3.2.3 Livelihood diversification, economic development, migration

Adapting farming practices, by e.g. diversifying crops and livestock, introducing drought-resistant varieties and species, altering rotations, integrating trees in cropping systems, and improving water management and irrigation, are strategies employed to diversify livelihoods in vulnerable geographies. These adaptations, alongside diversifying livelihood activities to include a mix of natural resource and non-natural resource based components, are particularly relevant in developing contexts due to their lower financial cost, but require knowledge and acceptance by local communities (IPCC 2022). Building knowledge about the benefits, trade-offs, and capacity to implement diversification that supports CRDP is a major enabler, as shown by a study on adaptation adoption factors in Nigeria (Kolapo and Kolapo 2023). In highlands, crops may be migrated from lowland to highland areas, as reported in Ethiopia's Semien mountains (Yohannes et al. 2020). In drylands, reducing wildfire risk through improved management strategies is a key focus, as observed in Australia's rangelands (Eldridge 2018). In island geographies, adaptation efforts may involve changing fishing grounds from nearshore to offshore or targeting different species, a strategy adopted by 75% of small-scale Tanzanian fishers, including those on Mafia and Zanzibar islands, over the past decade (Silas 2020). Adopting diverse adaptation practices can effectively mitigate climate change and foster development. In Nigeria, conservation agriculture and crop diversification have increased carbon sequestration (by enhancing nutrient cycling and incorporating varied root systems), improved yields, and significantly boosted farm income (Kolapo and Kolapo 2023). In highland ski areas, such as the French Alps, artificial snowmaking, diversification of tourism activities to non-snow activities, and shifting tourist seasons help maintain economic viability (Spandre 2019). Similar timing and location shifts in farming operations are observed in drylands, where adjusting planting, harvesting, fertiliser application, irrigation, and crop residue management timings can positively affect carbon sequestration (Spandre 2019). Global studies on regenerative agriculture highlight that early-season planting can enhance carbon uptake, while efficient fertiliser use reduces nitrogen losses (Khangura et al. 2023). Migration, either seasonal or permanent, is also used across geographies as a livelihood diversification strategy. It expands access to networks and resources, including training opportunities and jobs. A regional study on climate-induced migration in South Asia's highlands indicates that at least one household member has migrated, nationally and internationally, to work in the informal sector, with remittances boosting household income (Maharjan 2020). In drylands, pastoralists commonly adapt by migrating long distances to track variable and patchy plant growth to feed their animals (Homewood 2018). Such migration can generate indirect mitigation benefits (Gebeye 2016), as detailed in the next section.

3.2.4 Fostering integrated, mixed knowledge

Local agroecological and indigenous knowledge is a key determinant in decision making for climate change adaptation and mitigation across vulnerable geographies. It shapes innovation priorities and the adaptations undertaken, often promoting low-carbon practices. Indigenous and local communities typically have low carbon footprints, utilising construction materials with low embodied energy and relying on low-emission local food systems. Research on smallholders' agroecological knowledge in northern Morocco shows that local knowledge provides robust foundations for understanding adaptation decisions and can guide the scaling of climate adaptation and mitigation efforts (Kmoch et al. 2018).

Smallholders adopted diverse farming systems and agroforestry practices, such as tree-based diversification (increasing olive tree cover) and tree establishment in erosion channels in lowlands, serving as natural hard protection boosting carbon sequestration. In the highlands, tree grafting was used to increase carob tree yields. Drylands offer abundant local knowledge for climate change adaption and mitigation. In Ethiopia, pastoralists use a mobile, adaptive approach to cope with climatic uncertainty, which supports food production and sustains mitigation by preventing overgrazing, allowing pastures to recover, and maintaining healthy deep-rooted grasses that enhance carbon sequestration (Gebeye 2016). A study on indigenous and traditional knowledge in ecosystem-based adaptation across Pacific islands shows that communities have considerable natural resource management experience shaped by social norms, spiritual beliefs and colonial marginalisation (Nalau 2018). In Samoa, historical experiences shape local adaptation decisions, while in Vanuatu, gender differentiation affects the types of adaptation pursued. Men hold knowledge of traditional weather indicators for early warning or guiding planting times, while women are responsible for coastal planting decisions primarily for aesthetic purposes, rather than responding to coastal hazards (ibid.). Understanding and integrating these forms of knowledge into adaptation and mitigation efforts can help to address the root causes of unequal climate vulnerability (Williams et al. 2020). Fostering mixed knowledge to improve justice and equity is therefore a key CRDP enabler.

3.2.5 Disaster risk management and early warning systems

Monitoring and predicting climate events through early warning systems, along with vulnerability and impact assessments, enable adaptation by mobilising responses and prioritising long-term coping approaches. Key enabling factors include building institutions capable of implementing disaster risk management, ensuring adequate coordination among multiple stakeholders, guiding government-level planning and financing, and mobilising ground-level responses (Muto 2022). In the central Himalayas, the assessment of monitoring and early warning systems demonstrates that downstream communities have an increased capacity to mitigate the impacts of ice collapse and glacial lake outbursts due to in-situ, real-time information that provides advance alerts (Wang et al. 2022). A study on the impacts of a heatwave warning programme on mortality in dryland Australia compared extreme events in 2009 (without early warning) and 2014 (with public warning and awareness raising implemented that year). The 2014 event saw noticeably smaller mortality rates and fewer cardiac, renal and heat-related diagnoses (Nitschke et al. 2016). A cost-benefit analysis of a cyclone early warning system in Samoa shows that for every$1 invested, the system generated a return of $6, including avoided damages and production losses, and relief and rehabilitation costs (Fakhruddin and Schick 2019). While disaster risk management and early warning systems do not directly support mitigation, they can indirectly inform and influence climate mitigation policy and development planning.

3.2.6 Policy measures

A variety of policies aim to address climate change risks and impacts while fostering development, as detailed in the Nationally Determined Contributions (NDCs) submitted to the United Nations Framework Convention on Climate Change (UNFCCC) Secretariat by highland, dryland and island countries (Kissinger et al. 2019). Adaptation policies primarily focus on agriculture (crop and livestock diversification and management), flood management (disaster management, dam construction, and water channelling structures), coastal zones (protection from sea-level rise and extreme events), and water resources (building storage facilities, groundwater management, and rainwater harvesting), as observed in dryland sub-Saharan Africa (IPCC 2022; Nyiwul 2019). Mitigation policies across these geographies emphasise land use change (agroforestry to increase carbon sequestration), agricultural and livestock management (reduced tillage and improved livestock feed to reduce emissions), and energy efficiency and renewable energy (improving building insulation or providing access to renewable energy) (Dubash 2022). Marine emissions policies in island geographies regulate vessels' emissions, incorporate spatial planning to optimise vessels' routes, and incentivise eco-friendly shipping and green ports (Chou et al. 2021).

Figure 5 shows that an array of shared responses address the impacts identified across geographies, either directly (dark shaded cells) or indirectly (light shaded cells). For example, nature-based, land-based and ecosystem-based approaches (cell A in Fig. 5), hard protection (B), livelihood diversification (C), and policy measures (F) simultaneously address impacts on ecosystems and biodiversity, fisheries, agriculture and water systems, while reducing food insecurity, improving human health, fostering economic development and mitigating the migration and displacement impacts of climate change. They also indirectly address the remaining impacts (economic losses, migration and displacement, and transboundary impacts).

Drawing on the broad response categories in Sect. 3.2.1–3.2.6 Table 1 summarises the interplay between arenas of engagement across systems in pursuit of CRDP using illustrative cases.

Table 1's illustrative cases show that while the measures applied are similar across vulnerable geographies, their potential to foster CRDP depends on system-specific circumstances (the ways in which the arenas of engagement interact and are managed). These arenas incorporate the socio-cultural context, the political, institutional, economic and financial context, knowledge availability and technological capabilities. The enablers needed to progress towards CRDP are discussed in Sect. 4.

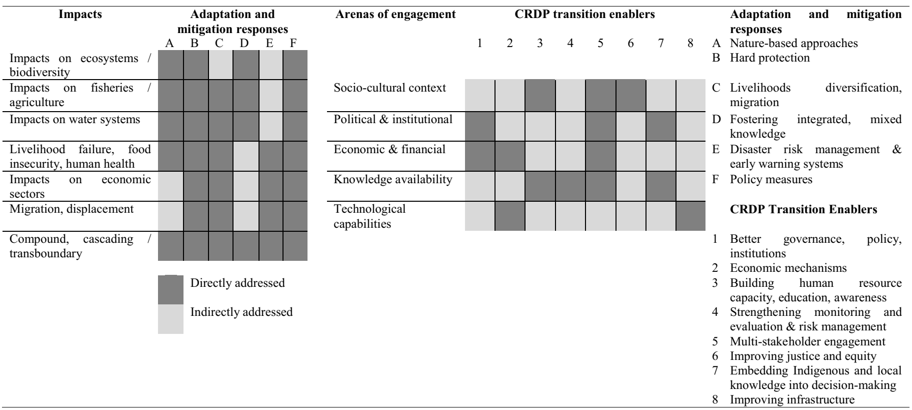

Fig. 5 Summary of adaptation and mitigation responses, arenas of engagement and CRDP transition enablers, linked to key climate change impacts across highlands, drylands and islands. Shaded cells show a direct contribution of a specific response or enabler to the impact or arena of engagement addressed

Table 1 Interplay between arenas of engagement in the pursuit of CRDP across illustrative vulnerable geographies

System category (see Fig. 1)	Highland / dryland / island	Dryland	Island / highland
Country	Italy	Nigeria	Papua New Guinea
Human Development Index 2021 (UNDP 2021)	Very high	Low	Medium
Adaptation and mitigation responses examined	Nature-based measures (no-tillage, fertiliser and water reduction), economic diversification (artificial snowmaking in highlands), dryland policy measures (Land Degradation Neutrality (LDN) targets), and integrated coastal management and erosion control (islands)	Nature-based measures (conservation agriculture -reduced tillage, maintenance of soil cover and crop rotation).	Nature-based measures (forest conservation) and livelihood diversification (crop diversification), policy and economic measures.
Socio-cultural arena	Non-financial factors drive adoption and continuation of adaptation and mitigation (de Leo et al. 2023): • Social factors: positive effect of peers' opinions about other farmers' adoption of responses. • Social pressure on innovation drives other farmers to meet the shared values of their peers.	Statistically significant factors influencing adoption of agricultural adaptations (Kolapo and Kolapo 2023): • Age: older farmers more inclined to adopt new approaches. • Gender: higher adoption by males with higher access to agricultural inputs and land. • Farm size: larger farm size enables higher implementation. • Education: higher education conducive to higher pursuit of mitigation measures.	Farmers' crop diversification choices in highlands and coastal areas are partially driven by climate concerns (Nordhagen et al. 2017). Diversification mostly pursued to sustain consumption and sale (female-driven), and for showing-off status through high value crops (male-driven). Clan power structures limit the ability to progress extension services and divert climate responses away from agroforestry towards cash crops (Baynes and Herbohn 2022).

Table 1 (continued)

System category (see Fig. 1)	Highland / dryland / island	Dryland	Island / highland
Political and institutional arena	• Italy features an array of policies and institutions focused on conserving its highland, dryland and island areas to promote sustainable development. Dryland-related policy measures include LDN target setting and mainstreaming in Italy's National Strategy for Sustainable Development (Chasek 2019). • Implementation of Italy's non-binding policies on sustainable development are hindered by a lack of administrative capacity (Pizzimenti and Di Giulio 2023), showing the importance of political dimensions in driving CRDP.	Implementation of climate change responses hampered by: • Widespread conflict triggered by poverty, political tension, rivalries in resource allocation across communities, ethnic and religious groups. • State and private sector interests (including agribusinesses and customary elites) in forested areas prioritised over natural resource conservation. • Weak protection of indigenous rights and of smallholder production systems.	Advanced climate adaptation efforts due to high political and institutional focus on climate planning and implementation, monitoring and evaluation, engagement in climate change scenario modelling, impact and vulnerability assessments, public awareness and stakeholder outreach (Robinson et al. 2019). The country's political economy shape the commitments made at COP21 and therefore its capacity to foster CRDP (Pascoe et al. 2019).
Economic and financial arena	• Lack of resource mobilisation on LDN translates into limited commitment to deliver policy outcomes conducive to adaptation and mitigation responses in drylands (Chasek 2019). • Considerable upfront investment enabled adaptation through artificial snowmaking in highlands, covering 90% of the country's ski slopes (Legambiente 2023).	Limited financial capacities to invest in large-scale mitigation or international climate finance initiatives. Reliance on international support, grants, or innovative financing mechanisms to implement adaptation and mitigation measures, but effectiveness hampered by corruption.	Effective capacity-building used to plan, implement and evaluate adaptation and mitigation responses makes it one of the best suited small island developing countries to advocate for higher levels of international climate financing. Such capacity gives the country strong potential to drive CRDP (Robinson et al. 2019).

Table 1 (continued)

System category (see Fig. 1)	Highland / dryland / island	Dryland	Island / highland
Knowledge and technology arena	• Structured access to knowledge on adaptation and mitigation practices, facilitated by awareness raising and provision of advice to farmers, translates into higher adoption of climate smart agriculture (Pagliacci 2020). • Climate smart agriculture stimulated through integration of environmental and technological factors, which affect farmers' profitability.	Adaptation and mitigation actions are higher across members of farmer associations, with access to extension services and up-to-date knowledge of technology.	Despite the effectiveness of landscape restoration through agroforestry to deliver adaptation, mitigation and development benefits, limited knowledge and the socio-cultural dynamics described above hamper knowledge sharing and adoption of new approaches and technologies into existing farming practices (Baynes and Herbohn 2022).

4 Discussion

The emphasis of AR6 on CRDP requires the advanced application of the concept. Examining CRDP in different vulnerable geographies provides a useful starting point given the urgency of climate and development action required in these systems. Our findings show that vulnerable highland, dryland, and island systems, including their overlapping combinations, face similar climate impacts. Loss of ecosystems and biodiversity, along with the degradation of fisheries and agriculture, have emerged as major shared impacts. Equally important are the impacts on water systems, such as decreased water availability for irrigation. From a socio-economic perspective, climate change exacerbates livelihood failure, human health degradation, vulnerability, insecurity, malnutrition, and deteriorates psychological wellbeing across all geographies. Reduced agricultural, livestock and fishing yields translate into economic losses and decreased income from tourism. These outcomes, combined with climate-induced displacement and migration, exacerbate the risk of conflict and trigger numerous compound, cascading, and transboundary impacts.

In applying the CRDP framing, focus on different vulnerable geographies proves useful in assessing localised trends and responses. Literature review and narrative analysis indicate that distinct solutions are often employed in different contexts. For example, structural hard protection is prioritised in highlands and islands, while nature-based protection is widely reported in drylands. Nevertheless, some responses can jointly address the impacts on ecosystems, water, food security, and livelihoods. Nature-based, land-based and ecosystem-based approaches, such as watershed management, afforestation, and agroforestry, are used across geographies, alongside livelihood diversification strategies such as diversifying crops and livestock, altering cropping schedules, or adapting tourism activities to changing seasons or snow patterns. Our conceptual framework enabled the assessment of current climate change impacts and adaptation and mitigation responses, facilitating discussion of their potential implications for shifting to future CRDP across highlands, drylands and islands. Adopting such an analytical lens (see Fig. 3) and addressing similar research questions in locally-focused case studies, e.g. involving specific geographies, or countries, regions, and vulnerable contexts can provide the empirical evidence urgently needed to inform CRDP in practice. Future research must consider how the identified adaptation, mitigation and development responses may evolve over time, linked to different warming projections, particularly considering multiple system transitions and the interlinkages between systems. While the solutions identified through the framework extensively cover transitions for land and ecosystems, and urban and infrastructure systems, future focus could be expanded to better capture other transition areas, such as energy and industrial systems.

While the IPCC advocates for the operationalisation of CRDP, proposing specific measures is challenging because different geographies and groups within the same geography require tailored support (Adenle 2017). As shown in Fig. 5, this research has emphasised the need to shift away from individual responses towards a multifaceted array of measures that tackle common impacts and drive wider transitions. The availability and effectiveness of such measures depends on the unique circumstances of each context, shaped by the five arenas of engagement. The arenas not only influence the effectiveness of the measures, but also shape the context in which vulnerability is initially generated. Our findings support the hypothesis that the nature of the underlying vulnerabilities, characterised by their arenas of engagement, matters more than the characteristics of different geographies in defining both CRDP and the key enablers of those pathways.

The socio-cultural context shapes the adoption of adaptation and mitigation responses, driven by factors such as age, gender, education levels, power structures and religious beliefs (Table 1). This suggests that community understandings and acceptance of innovative climate responses are key for enabling CRDP. Literature on drylands and islands shows that community cohesion and socio-cultural drivers can be strengthened by enhancing engagement and cooperation between practitioners and communities. In forestry projects in Madagascar, this was achieved by empowering informal organisations led by villagers to foster community trust, providing agricultural training, and employing locals (Favretto et al. 2016). Studies on community building through ecosystem-based approaches in mountains show that peer-to-peer learning networks enhance local capacity to connect upstream and downstream water user groups (Klein 2019). This underscores the need for a disaggregated view within small communities to identify approaches that consider disparities and inequalities shaping interactions among actors. Improving justice, equity, and gender considerations in policy, institutions, and everyday practices creates opportunities for CRDP, as the root causes of climate vulnerability often stem from poverty, marginalisation, and exclusion (Goodrich et al. 2019). Moving beyond single impacts and embedding indigenous and local knowledge into decision-making strengthens the capacity to address multiple impacts, as shown by a systematic review of knowledge integration in landscape research (Williams et al. 2020). Successful knowledge diversification requires meaningful engagement of multiple stakeholder groups, through inclusive consultations and integrated landscape management, grounded in indigenous, local and traditional knowledge (Favretto et al. 2020).

Different vulnerable geographies have their unique policies, institutions, and governance approaches which vary in content, ambition, enforcement, and participation, influencing the adaptation, mitigation and development responses implemented. Adaptation policies focused on flood management may facilitate disaster management or the construction of water channelling structures, while coastal zone protection policies help to cope with sea-level rise and extreme events (Reguero 2018). By stopping erosion and conserving natural floodplains, these policies can enhance carbon storage and generate wider CRDP benefits, decreasing vulnerability to future extreme events, lowering potential damage and protection costs, and sustaining economic activities in high-risk areas (Aggarwal et al. 2021). Agricultural policies promoting crop and livestock diversification can stimulate emissions reduction by supporting reduced tillage and grass regrowth, and by improving livestock feed (Chen et al. 2021; Kolapo and Kolapo 2023). These impacts are more significant when focusing on land use change, such as using agroforestry to increase carbon sequestration (Dar 2023). From adaptation and development perspectives, behavioural changes and economic measures such as crop insurance and feed subsidies can reduce water consumption and improve environmental management, potentially improving livelihoods and socio-economic well-being (Premand and Stoeffler 2022). Experiences with climate risk insurance in Pacific Small Island Developing States show the key role of insurance mechanisms in sustaining informal economies and the livelihoods of vulnerable populations, particularly during recovery and reconstruction following extreme weather events (Jain et al. 2022). Integrating insurance premiums with mitigation responses has proven effective in encouraging insured households to reduce their emissions (ibid.). Additionally, banks are increasingly offering incentive loans with reduced interest rates to farmers and forestry industries that reduce emissions or enhance their socio-environmental and governance performance, for example by increasing the transparency of biodiversity reporting (BNDES 2021).

In moving toward CRDP, the scale of governance systems often differs from the scale of ecosystem operation (Vatn and Vedeld 2012). The scale(s) of governance are crucial, as solutions are specific to sub-national local areas where governance interplays horizontally and vertically, and impacts depend on the interplay between different actors and institutions. Identifying policy synergies and focusing on the multi-faceted linkages between actors and sectors within a political system is key to widening opportunities to pursue CRDP. Table1showed the importance of the politics, governance, and institutions as arenas in which different groups interact, determining the institutionalisation of CRDP (Pizzimenti and Di Giulio 2023). Since 2014 Italy (highland/dryland/islands) has used Land Degradation Neutrality (LDN) as an overarching framework aimed at avoiding, reducing, and reversing land degradation to maintain ecosystem health and build resilience (adaptation), reduce pressure on forests and agricultural areas (mitigation) and improve socio-economic wellbeing (development). Targets were set using land cover, productivity, and soil organic carbon indicators in line with international reporting requirements (Dallimer and Stringer 2018) and were integrated into Italy's National Strategy for Sustainable Development for achieving the national Agenda 2030. However, after nearly a decade of attempts to institutionalise LDN, the paradigm remains vague and non-binding (Chasek 2019). Slow institutionalisation is also observed in the Italian National Plan for Adaptation to Climate Change, first published in 2022 with a four-year delay, and approved in 2023 (MEES 2022). Organisational reforms and resource mobilisation are needed for the political system to effectively institutionalise CRDP (and LDN), even when formal policies and institutions are in place.

Different geographies have varying financial capacities to invest in CRDP. More economically developed geographies, such as Italy's highlands (Table 1), can afford substantial investments in large-scale artificial snow-making infrastructure to adapt changing snowfall, with ski resorts investments accounting to several million Euros (Legambiente 2023). In 2022, Italy accessed €5.5 billion in international loans for renewable energy and decarbonisation projects, which leveraged an additional €34 billion from private and public sectors, supporting over 82,500 small and medium-size businesses, and driving substantial economic development (EIB 2023). In contrast, poorer geographies like northern Nigeria's drylands (Table1) have limited financial capacity for adaptation and mitigation, heavily relying on international donor support, with effectiveness often hampered by political conflicts and corruption. Similar financial constraints are observed in the financing needs to achieve NDCs across Small Island Developing States (Mohan 2023). Economic mechanisms, such as adaptation and mitigation finance (e.g. carbon pricing), subsidies and tax incentives, climate-focused insurance, and public-private partnerships, are major enablers of CRDP but must be integrated to address adaptation and mitigation simultaneously (ibid.). In the Sahelian drylands, integrating insurance mechanisms, financial services, savings programmes, and cash transfers into policy increased the benefits from drought responses (Premand and Stoeffler 2022). This approach also improved water management and conservation, enhanced carbon sequestration through soil restoration, and built community resilience by increasing savings and asset accumulation, allowing greater livelihood diversification.

Access to economic mechanisms and institutional support is better secured when adequate human resource capacity, education, and awareness are built. Carbon projects designed for mitigation and rural development in Madagascar underscore the importance of enhancing community understanding of available economic mechanisms, and the carbon sequestration benefits of forest restoration projects. Understanding fosters trust and cooperation, building a sense of environmental stewardship (Favretto et al. 2016). Public advocacy and social media campaigns on topics like water use efficiency or climate-smart agriculture can similarly contribute to CRDP by stimulating behavioural changes, such as reducing water consumption or adopting sustainable agriculture. Embedding diverse knowledge into decision-making processes is crucial across all arenas of engagement.

Highland, drylands and island geographies feature diverse technological capabilities. More developed systems can adopt adaptation and mitigation approaches grounded in cutting-edge technologies. Impact assessments of technological innovation through renewable investments in small off-grid Italian island systems show the importance of understanding the effects of technological innovation, and the competitiveness of alternative technologies in achieving mitigation benefits, adaptation, and development under climate uncertainty (Giudici et al. 2022). Conversely, less developed systems often rely on lower-cost solutions, such as community-based adaptation, with less scope for pursuing mitigation. This is evident in low-income highlands, where households with low economic status can only adapt to water stress by reducing water consumption and fetching water from distant sources, rather than upgrading to more efficient water management technologies (Rasul et al. 2020). In contrast, financially secure households who have access to adequate technology can reduce their vulnerability by purchasing water or building storage infrastructure to improve their capacity to collect and store water. Enhancing infrastructure is a key enabler for CRDP. Infrastructure improvements in coastal areas can enhance resilience to extreme events and address rapid urbanisation, especially where the majority of the population and economic activities are located in low-elevation costal zones. Additionally, improving energy systems can foster mitigation by decreasing islands' reliance on volatile fossil fuel markets and creating new jobs (Esteban 2020). Overall, the complexity of local and contrasting political dynamics in less developed systems is often exacerbated by international power dynamics, which may limit resource mobilisation and transfers of adequate technology and infrastructure. Fair, adequate and transparent mobilisation of climate finance and technology is key to enable long-term transitions toward CRDP.

Navigating the CRDP dimensions and arenas of engagement requires that the adaptation and mitigation responses adopted to address a specific set of impacts do not decrease the potential linked to other impacts. This is evident in the Italian case, where artificial snow-making adaptations generated conflicting outcomes. In low altitude Monte Cimone ski resort, the effectiveness of artificial snow-making during the 2022 ski season was hampered by temperatures not falling below freezing. Some authors argue that trade-offs between Italian highlands and drylands may arise because the water needed for snow-making in the mountains conflicts with the increasing water demands in the surrounding drylands due to rising drought levels (Assennato 2020). Regarding mitigation, Italy relies on hydropower as a significant renewable energy source. Such water trade-offs impact its capacity to pursue carbon- neutral energy trajectories. These impacts are spread across the highlands, as 70% of Italy's ski slopes rely on artificial snow.

Expanding on the findings of Wilhite and Pulwarty (2018), we highlight the need for responses that are integrated both horizontally (across actors) and vertically (across systems), particularly where short-term crisis management may increase longer-term vulnerability by reiterating and reinforcing past water and land management practices that originally created these vulnerabilities. Adequate monitoring and evaluation play a major role in overcoming data deficiencies in designing coordinated CRDP, filling knowledge gaps, and informing implementation of adaptation and mitigation responses

(McDowell 2020). As shown in Mediterranean drylands and islands, robust drought policy must include adequate monitoring, early warning, and risk management that integrate mitigation, adaptation, and development needs across sectors (Wilhite 2019). Pursuing CRDP goes beyond addressing climate and environmental change as a single objective. It entails identifying and implementing adequate response measures that reduce exposure to risks, creating more resilient and sustainable socio-ecological systems. In South Africa, a national monitoring and evaluation system on climate change tracks the country's advances toward a low-carbon economy and climate-resilient societal transition (Republic of South Africa 2021). The system monitors data on emission reductions, climate change trends, and the impact of adaptation and mitigation actions, aiming to continuously adapt and inform implementation across the country's highlands and drylands.

Monitoring supported by inclusive CRDP relies on multi-stakeholder engagement that aligns the diverse needs of stakeholder groups, stimulates mutual learning, and promotes the participation of the most marginalised groups across geographies. Social network analysis in the degraded dryland landscape of Machubeni, South Africa, shows that inclusive participation strengthened collaboration among government departments, local actors and researchers, leading to improved knowledge sharing and coordination of mitigation and adaptation actions. It has increased community well-being, and enhanced the potential for upscaling CRDP (Falayi et al. 2020). The need for cross-scalar CRDP partnerships among multiple stakeholders is also evident across the Himalayas, as mountain ecosystems are typically transboundary and climate impacts transcend jurisdictions (Mishra 2019). This requires regional cooperation among countries or transboundary governance to jointly identify future pathways in securing adaptation, mitigation, and development.

5 Conclusion

This paper has explored CRDP across multiple vulnerable geographies (highlands, drylands and islands), identifying opportunities for action. A novel conceptual framework was developed to assess the shifts from present climate change impacts and adaptation and mitigation responses to future CRDP. The findings show the need to pursue mixed and interlinked measures that tackle common climate impacts across geographies, driving wider system transitions toward CRDP. While specific adaptation and mitigation responses should be tailored to local contexts, different geographies and groups may require emphasis on different types of enabling conditions. Specific combinations of governance features (e.g. stakeholder engagement, community participation, multi-level integration) and assets (e.g. finance, knowledge, technology, infrastructure) that target the major underlying vulnerabilities are crucial in shaping the necessary emphasis on each enabler to operationalise CRDP. In adopting these enablers, responses aimed at addressing a specific set of impacts should not decrease the capacity to adapt to and mitigate other impacts. Integrated responses to climate change are essential to move along CRDP, where the arenas of engagement need to foster better governance, policy, and institutions, strengthen economic mechanisms, support monitoring and evaluation, build human capacity, and encourage multi-stakeholder engagement. These efforts can overall improve justice, equity, and infrastructure. They also play a central role in shaping underlying vulnerabilities, more so than the exposure of the vulnerable geographies themselves to climate impacts.

Appendix

Table 2 Number of scientific papers identified and reviewed across the IPCC Working Group II's Sixth Assessment, Scopus and ScienceDirect

Source	Number of papers identified	Number of papers reviewed
IPCC Working Group II's Sixth Assessment	1,906 • 574: highlands • 512: drylands • 820: islands	-
Scopus	5,812	-
ScienceDirect	28,936	-
Total	**36,654**	**109**

Table 3 Climate change impacts identified across highlands, drylands and islands and key literature

Impacts on socio-ecological systems	References
Impacts on ecosystems/biodiversity	Manes et al. 2021, Salmon et al. 2019
Impacts on fisheries/agriculture	Hussain et al. 2018, Tsymbarovich et al. 2020, Robinson et al. 2020
Impacts on water systems	Viviroli et al. 2020, Choukri 2020, Karnauskas et al. 2018
Livelihood failure, food insecurity, degradation of human health/inequality	Motschmann 2020, Hussain 2019, Clayton 2020, Goudarzi et al. 2017, Myers 2017, Hickey and Unwin 2020, McCubbin et al. . 2015
Impacts on economic sectors, tourism/recreation	Spandre 2019, Favretto et al. . 2021, Murray et al. 2021
Human migration, reduced habitability, displacement/conflict	Dasgupta et al. 2022, Kinouchi et al. 2019, French et al. 2015, Almer et al. 2017
Compound, cascading/transboundary impacts	Pescaroli and Alexande 2018, Wandres et al. 2020, Goudie 2020, Russell et al. 2017, Bebber 2019

Table 4 Adaptation and mitigation responses identified across highlands, drylands and islands and key literature

Adaptation and mitigation-related responses	References
Promoting nature-based, land-based and ecosystem-based measures / approaches	Dar et al. 2023, Amadu et al. 2020, Aggarwal et al. 2021, Kattumuri et al. 2017, Buisson et al. 2019, Reed et al. 2015, Förster et al.2019, Hughes et al. 2017, Estrada-Carmona et al. 2014
Hard protection	Chidi et al. 2022, Reguero et al. 2018, Crichton and Esteban 2018, Ahmed et al. 2016
Livelihoods diversification, economic development, migration	Yohannes et al. 2020, Eldridge and Beecham 2018, Silas et al. 2020, Spandre et al. 2019, Maharjan et al. 2020, Homewood 2018
Fostering integrated, mixed knowledge	Kmoch et al. 2018, Gebeye 2016, Nalau et al. 2018
Disaster risk management and early warning systems	Wang et al. . 2022, Nitschke et al. 2016, Fakhruddin and Schick 2019
Policy measures	Dubash et al. 2022; Kissinger et al. 2019

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Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication The manuscript has been approved by all authors for publication, and the work described is original research that has not been published previously.

Conflict of interest The authors declare no competing interests.

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