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Original Article

Climate Change Adaptation Strategies: Pathways to a Resilient Future

Kiran Dilip Londhe[1], Dr. N. I. Dhayagode[2]
[1]Research scholar, Walchand college of Art's and science solapur
[2]Assistant Professor, Walchand college of Art's and science solapur

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Correspondence Address:
Kiran Dilip Londhe
Research scholar, Walchand college of Art's and science solapur
Email:
Kiranlondhe22@gmail.com

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Abstract

Climate change presents unprecedented challenges to ecosystems, human health, economic stability, and global development. While mitigation efforts are crucial to reduce greenhouse gas emissions, adaptation has become an equally urgent priority to address inevitable climatic impacts. This paper reviews the scientific basis, impacts, and socio-economic consequences of climate change, and outlines comprehensive adaptation strategies across key sectors including agriculture, water resources, urban planning, health, and biodiversity conservation. Emphasis is placed on principles of effective adaptation, community-based approaches, indigenous knowledge, governance frameworks, technological innovation, financing mechanisms, and monitoring and evaluation systems. Through case studies of both successes and failures, the paper highlights lessons learned and future directions for resilient and sustainable development. It concludes that adaptive capacity, resilience-building, and integrated policy approaches—supported by inclusive governance and innovation—are essential pathways to a climate-resilient future.

Keywords: *Climate change, Adaptation strategies, Resilience, Sustainable development, Biodiversity conservation, Community-based adaptation, Indigenous knowledge, Climate governance, Technological innovation, Policy frameworks, Water resource management, Climate finance*

Introduction

Addressing the causes and consequences of climate change is widely recognized as one of the paramount global challenges threatening ecosystems, infrastructure, economic development, and human well-being. Global mean surface temperature has already increased by 1 °C, while sea level has risen by 20 cm over the twentieth century, accompanied by a broad range of other climate changes that adversely affect human and natural systems. Climate change impacts, such as extreme hydrological events, reduced water availability, and agricultural production losses, have significant socio-economic consequences with detrimental feedbacks to global functioning. Resulting climate change impacts affect economic growth, hinder poverty reduction, and exacerbate already existing development problems.

While mitigation—the reduction of greenhouse gas (GHG) emissions—is critical, adaptation is also necessary, particularly because large changes in climate are unavoidable over the coming decades. Anticipative climate-change adaptation provides a valuable option to moderate many of these consequences and limit the cost of climate-change impacts. Mitigation and adaptation are complementary strategies, which should be considered simultaneously, especially when long-term development is at stake, as with infrastructure projects (S. Colgan et al., 2016).

Building adaptive capacity and implementing adaptation strategies therefore becomes fundamental, the challenge is now "how best to adapt". A number of options exist at a variety of temporal and spatial scales, with different costs and trade-offs across scales. This work reviews extant literature on adaptation, highlighting fundamental principles to guide the development of an effective portfolio of policies and measures and the major strands emerging across sectors, before examining the importance of community-based approaches. It proceeds by assessing policy frameworks, technology, and financing issues—recognizing the enabling role of appropriate governance—and evaluates methods for monitoring, evaluation, and assessment (Papadimitriou et al., 2019). It concludes by outlining promising avenues for future response and laying out the principles for a resilient and sustainable pathway to the future (Warner et al., 2018).

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Understanding Climate Change

Climate change, a consequence of anthropogenic augmentation of heat-trapping gases, particularly carbon dioxide, impacts Earth's climate system at regional and global levels and permeates all components of societies and ecosystems. The IPCC Fourth Assessment Report projects an increase of temperature in the range of 1.5–4.5 °C by 2100, with concomitant changes in precipitation, humidity, winds and ocean currents, plant hardiness and sea level rise, and the frequency and magnitude of extreme weather events. Agents of change such as climate coexist with other external forces often operate on diverse spatial and temporal scales, such that climate change and its impacts cannot be understood in isolation. In turn, these changes affect human health and activities, biological diversity, global food production, water availability, ecosystem production and services, and land use planning. Climate-change adaptation strategies therefore require assessment and evaluation not only of the economic and environmental impacts, but also of the technological and political responses.

Noise and uncertainty in the climate system, and the narrowness of regional and local-scale assessments from global models, complicate the attribution of observed changes to research adequate to support measured responses. Updating of scenarios and continuing enhancement of resolution and process integration at broad scales need to be accompanied by organized utilization of advances at local scales with, for example, more detailed or enhanced coverage of local land use and sea surface phenomena. An additional complication comes from a number of rapid changes observed in the past decade; many of these are directly or indirectly related to atmospheric or ocean circulation and climate patterns. Of particular note in this context is recent recognition of the strength of forcing by both positive feedbacks and hitherto unconsidered factors such as interactions within the Arctic system (Shan, 2018).

The effect of human activities on the climate system raises two issues: the ability of human societies to adapt to the changing climate and the degree to which adjustments can be made in the pattern of human activities to alleviate the causes and consequences of climate change. Adaptation to long-term changes in the climate system constitutes an ever-present facet of human existence, as individuals, communities and governments organise and re-organise societies in a never-ending interaction with the habitats and environs within which they reside. While adaptation, and the associated management or adjustment processes, are by no means modern phenomena, adverse climate-related effects nevertheless carry the proviso that societies have not yet undergone the natural range of change experienced in recorded history, implying a different regime and possibly different response mechanisms to such change (A. Fisichelli et al., 2016).

1. Scientific Basis of Climate Change

The fundamental basis for understanding climate change from an Earth-system perspective is the global energy balance (A. Fisichelli et al., 2016). Earth's energy budget is determined by the balance between incoming solar energy and the amount of energy reflected or emitted back to space. This balance drives virtually all physical, chemical, and biological cycles on the planet. Variations in Earth's orbit throughout its history have caused global climate oscillations between glacial and interglacial periods and numerous regional and global climate change episodes. Currently, elevated levels of greenhouse gases—primarily carbon dioxide, methane, and nitrous oxide—are absorbing a portion of Earth's outgoing thermal infrared radiation, causing a planetary energy imbalance that manifests as global warming (M. West et al., 2009).

Two important principles are useful for evaluating the character and magnitude of future climate change. First, the radiative effects of multiple greenhouse gases are nearly additive, which facilitates aggregation into a common metric. Radiative forcing is defined as the difference between solar energy absorbed by the Earth and energy radiated back to space. Second, there is a relatively short time lag between the imposition of a radiative forcing and the corresponding adjustment of the Earth's temperature. Although the climate system will continue to respond to recent greenhouse-gas emissions for many years, some of the projected climate changes are already effectively "locked in" by past emissions. Energy-balance considerations alone suggest that the amount of climate change expected during the twenty-first century will be very large—indeed, significantly larger than any comparable change in at least the past 10,000 years—and this supports other lines of evidence pointing to the urgency of understanding potential future climates.

2. Impacts on Natural Systems

The broad spectrum of climate-change impacts on natural systems poses serious challenges globally (M. West et al., 2009). Changing climate regimes and extreme events—including heat waves, fires, droughts, heavy rainfall, and floods—have the potential to shift ecosystem states, decrease species diversity further, alter carbon and nutrient cycles, and enhance the spread of alien invasive species and diseases. Changing temperatures, precipitation, and snow cover already affect biodiversity, in the timing of reproduction, flowering, migration and hibernation, and the distribution and abundance of many species. Natural systems with more ecological resilience—where there are more species with different responses to climate—will suffer less, but biomonitoring programmes similar to those run for the Paris Agreement and the Millennium Development Goals will be needed to separate anthropogenic climate-change effects from background variability. Most ecosystems can adapt to higher rates of climate change if other stresses such as land-use transformation, toxic contamination, eutrophication, and alien species are controlled. But the efficacy of adaptation for some species depends on the availability and connectivity of suitable habitat (Papadimitriou et al., 2019).

3. Socioeconomic Consequences

Climate-change impacts are likely to have important consequences for human development and poverty alleviation (Papadimitriou et al., 2019). They are

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also a core concern of agricultural development, since global warming is increasing the global 'yield gap' — the difference between actual and potential crop yields (Theokritoff et al., 2023). Under conditions of climate change, it is also estimated that global fish supplies could decrease by 30% by 2100. Rural and low-income populations living in developing countries frequently face the greatest difficulties, because they have limited capacity to adapt. For example, where minimum heat-wave return periods decrease below the expected speed of recovery of heat-vulnerable crops, agricultural production capacities may fall sharply in the next decades. In the absence of adaptation, the extent of such disruptions is much greater than that of climate-change impacts under a high emissions scenario (relative to stability under a present-day climate) owing to the combined effects of socio-economic evolution and climate change. Without adaptation, the endpoint conditions of several Important Bird Areas, comprising an estimated 16% of remaining global terrestrial vertebrate diversity, would be outside contemporary temperature and rainfall margins under the high emissions scenario. By 2100, climate-change impacts on forest suitable climate are assessed as twice as large with socio-economics relative to today.

Constraints on adaptation include the long-term commitment to climate change, coupled with limited technological change, biophysical limits and economic costs. Constraints can be hard or soft, depending on the possibility of overcoming them in the longer term. Several dimensions of adaptation potential suggest equitable access to resources (income, education and governance) for the most vulnerable groups. Many human systems will face hard adaptation limits, despite the inclusion of many potential future technological change options in assessments.

Framework for Adaptation Strategies

Climate change adaptation refers to efforts undertaken to reduce the vulnerability of human and natural systems when adverse effects of ongoing or projected climate change impacts are anticipated (Muntasir, 2017). Adaptation strategies are essential to facilitate the maintenance of ecosystem integrity and sustainable delivery of ecosystem services, enabling people to sustain their livelihoods, safety, and well-being in the face of a changing climate (Galappaththi et al., 2019). Adaptation activities seek to facilitate societal transformation toward sustainability and resilience (A. Fisichelli et al., 2016).

The approach to climate change adaptation is shaped to a great extent by societies' worldviews regarding the environment and the degree of adaptive capacity available. Six general considerations guide the design of any climate change adaptation strategy:

- Adaptation represents a series of steps that arise through a process of analysis and planning; not a single event or outcome.
- Effective adaptation strategies depend on making well-informed decisions where clearly structured analytical methods and procedures facilitate the integration of climate and socio-economic information.
- Both autonomous and planned adaptations may be used to address climate risks as an integrated response to climatic and non-climatic parameters.
- Vulnerability assessments provide reliable indications of adaptation needs at both the sectoral and regional scale that are intended to guide adaptation planning.
- An effective response is often one that incorporates a variety of policy instruments.
- Adaptation measures include policies, projects, and technologies already being implemented at regional and sectoral levels.

1. Defining Adaptation

The physical impacts of a changing climate are both visible and measurable (A. Fisichelli et al., 2016). The atmospheric concentration of carbon dioxide, the principal greenhouse gas, has increased from a pre-industrial level of about 280 parts per million by volume (ppmv) to 385 ppmv in 2008. Climatic changes observed during the past century that exceed any in the previous 1000 years have increased the frequency and intensity of floods, storms, droughts, and fires. A range of terrestrial, freshwater, and marine species and assemblages have been affected by recent climates, including changes in distribution, seasonal events, migration patterns, and biological processes.

Adaptation efforts to meet the threats imposed by climate change actions (Papadimitriou et al., 2019) are classified in three general types: anticipatory, concurrent, and reactive or forced. Anticipatory actions take place before impacts; concurrent are actions implemented at the time of impacts; and reactive actions take place after the impacts. Additional classifications separate adaptation and mitigation based on the action that is taken, distinguishing between either of two general categories: structural and non-structural, where the effects of the response are either direct or indirect, and autonomous versus planned, where the adaptation is either spontaneous or deliberately planned. Adaptation strategies are likewise classified into three major categories. Those that assist natural adjustments to actual or expected climate impacts; those that reduce the vulnerability of human systems; and those that facilitate the transformations of or changes to new systems with lower levels of vulnerability. Adaptation is a general response option to reduce the vulnerability of natural and human systems to actual, expected, or projected climate change effects. It uses socio-economic measures and technological changes to reduce potential damages or to benefit from opportunities associated with climate change impacts. In the face of such projected changes, adaptation is urgently needed to reduce the vulnerability of natural and human systems and to build resilience to respond to a changing climate. Resilience is the capacity of socio-economic and ecological systems to cope with a hazardous event, trend, or disturbance by responding in ways that maintain their essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation. Adaptation strategies for climate change must contribute to the resilience and sustainable development of these natural and human systems.

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2. Principles of Effective Adaptation

Adaptation is a process of deliberate change in anticipation of or in reaction to changing climatic stimuli. Anticipatory adaptation occurs before impacts are evident, whereas reactive adaptation is a response to experienced changes. Adaptation may be incremental, comprising small adjustments that keep systems functioning within an existing framework, or transformational, involving fundamental changes that allow systems to reconfigure and meet new conditions. Because the climate already affects society and will continue to do so, the need for adaptation is immediate, and effective solutions will rely on transforming development pathways (M. West et al., 2009). Adaptation can be framed with three interacting principles: climate risk, adaptation pathways, and sustainability or development (Shan, 2018). Figure 3.3 illustrates these principles and their components.

Sector-Specific Adaptation Strategies

Adaptation strategies are likewise differentiated by sector in order to follow a sector's unique exposure, specific and evolving vulnerabilities, and the breadth and limit of potential responses. For example, for agriculture, strategies include crop management, water management, land management, diversification, and pest and disease management. For water resources, strategies include management of demand, supply, and water quality; storage, infrastructure, and operations and planning; as well as institutional changes and capacity building. For urban environments, there is planning and infrastructure and the detection, assessment, and early warning of storm surge and floods. For health, relevant strategies include health surveillance and monitoring, improving vaccination, food safety, and development of specific health-care plans, services, and infrastructure. And for biodiversity conservation, strategies include conserving and restoring ecosystems, protected area planning and management, ex situ conservation, and adaptive management (Papadimitriou et al., 2019). With a particular focus on sustainable development, trade-offs are assessed from micro-sector to multi-sector scales in order to provide a comprehensive and coherent evaluation. All of the integrated evaluations assume that the current climate policy achieves the 2 °C target of the Paris Agreement, yet trade-offs remain robust and even intensify among equitable community and natural capital objectives. Plausible pathways for a comprehensive, multi-sectoral, and climate-resilient response are discussed in the context of sustainable development goals.

1. Agriculture and Food Security

Agriculture underpins human well-being while also releasing greenhouse gases. Rain-fed cereal production in tropical, semiarid regions could decline by 50% by 2020, affecting incomes and food security. Adaptation pathways that connect at the landscape scale could enable transformation towards sustainability and resilience. Anticipated changes in climate are likely to intensify the challenge of feeding a growing global population, exacerbating existing pressures on the world's food systems and undermining progress on poverty reduction and sustainable development. Agricultural food production will have to increase substantially to meet rising demand, even as climate change is expected to reduce yields of major food staples. Food security will be threatened by price volatility, changes in water availability and access, and increased competition for productive land.

Key strategic investment priorities will promote technologies and policies to enhance adaptation and resilience, reduce emissions and increase productivity, and improve farmers' access to information, finance and markets. An integrated approach focused on agricultural productivity, food security and low-carbon development will contribute to economic growth, development and poverty reduction, while enabling transformational adaptation pathways focusing on climate-resilient food systems and landscapes. Adaptation strategies will also need to address the interaction of multiple stressors, including changes in temperature and precipitation, sea-level rise and salinity, increases in heat and drought extremes, and increased input and output price volatility (María Loboguerrero Rodriguez et al., 2018).

2. Water Resource Management

Water is under increasing pressure from climate change due to the mounting demands of a growing population and intensified hydrological cycles (Solaymani, 2018). Adaptation strategies and policies aim to increase the long-term resilience of freshwater governance to changing climate conditions (Drieschova & Eckstein, 2014). Adaptation strategies related to water resources range from low-regret measures to transformative adjustments, and ultimately to a redefinition of the fundamental premises underpinning existing water-resource policy. Integrated water resources management (IWRM) provides a useful framework for implementing adaptation, but the linkages with climate change remain fragile and preliminary. Water-resource managers will have to further develop adaptation strategies and policies based on the increasing evidence and scenarios emerging from climate-impact studies. These strategies include climate-change-proofing and contingency planning to early support of water-resource adaptation.

3. Urban Planning and Infrastructure

Urban areas constitute important greenhouse gas sources and sinks because of their associated population density and industrial and agricultural activities. Planning will increasingly focus on the stabilization of greenhouse gas concentrations. Questions arise regarding low-carbon, 'climate-proof' settlements in terms of urban form and infrastructure, challenges to effective planning for such development, the implications for governments at transnational to local levels, intergovernmental relationships, risk allocation, and the consequences for equity and social development. Climate change, as a global public good, raises complex planning issues that exceed traditional planning frameworks and the policy objectives of local authorities. A major constraint is the limited availability of climate change impact data at regional and local scales; existing models primarily provide insights concerning average climate parameter changes over large

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geographical areas and long time frames. While evaluating mitigation policies is facilitated through measurements of greenhouse gas emissions over time, assessing adaptation strategies—aimed at avoiding negative effects—remains difficult due to high uncertainty. Further research is needed to clarify the relationships between energy demand, land-use changes, and climate change. An interdisciplinary approach, involving planners, is required to fully address the environmental, urban, and social problems induced by climate change (Hagen, 2016). Between 1950 and 2030, the share of the world's population living in cities is projected to increase from 30% to 60%. Cities serve as engines of capitalist growth, attracting individuals seeking higher living standards; this trend stimulates demand for electricity, transportation, and larger homes. Low- and middle-income nations now host three-quarters of the urban population, the majority of whom face elevated risks from storms, flooding, landslides, and heat waves associated with climate change. Accordingly, governments must implement adaptation measures with a level of urgency and resource commitment that may exceed the strategies suggested by the IPCC. Urban planning can incorporate substantial adaptive and mitigative capacities, for example by reducing stormwater runoff, deploying energy-efficient and renewable technologies, and creating green spaces—such as green roofs—to mitigate the urban heat-island effect. Infrastructure and services provided by governments and the private sector—including early warning systems, emergency responses, regulated buildings, piped water, sewers, roads, electricity, and drainage—shield most urban residents from extreme weather events. These services are generally affordable and require minimal individual effort and knowledge to manage, although mechanisms for lodging complaints typically exist. Additional policy instruments—such as carbon pricing, taxes, and incentives for environmentally responsible lifestyles—can further reduce emissions (Ranasinghe & Gammanpila, 2015).

4. Health and Wellbeing

Climate change will affect the health and wellbeing of all populations over short and longer terms, albeit in varied ways and intensities. Addressing climate-change risks to health is thus one element of a multi-dimensional and ongoing response to climate change and its associated effects (J. Bowen et al., 2013). Climate change poses direct risks to physical health and life and indirect risks to income, food security, shelter and social infrastructure, with all consequences having significant implications for quality of life and psychological wellbeing. Indirect effects via disruption of social and economic systems may often be more significant than direct effects, but the latter are often better documented (Pourzand et al., 2023). A range of sectors is also responsible for implementing adaptive policies and measures to address risks to health and wellbeing, including health services, water and sanitation, trade, agriculture, disaster management and development.

5. Biodiversity Conservation

Climate change threatens species, ecosystems and cultural-heritage resources distributed throughout landscapes, seascapes and the atmosphere. Conserving biological diversity is a balancing act involving timely adaptations to change while simultaneously reducing the rate of loss of species, populations and communities, and providing resources for other sectors and society. Although the challenge extends well beyond protected areas, they provide a useful and practical focus for the development and implementation of adaptation responses. Climate-change-related vulnerability assessments provide a guiding framework for prioritizing sites and values at risk (Jacobs et al., 2019).

Climate change is modifying habitat, altering ecosystem functioning, driving species redistribution, facilitating invasions and increasing the risk of extinction. Through shifts in fire regime, drought, flooding and ocean salinity and chemistry, it also affects the ability of ecosystems to provide resources for human consumption and use. In addition, changes to the biophysical environment may affect the manner and extent of use, risk and understanding of place, and ultimately modify the cultural and social values of ecosystem services. Although it remains difficult to reliably predict the ecological consequences of climate change, it is widely accepted that they have already commenced and that the cost of inaction or limited action is likely to be very high.

The greatest risk facing biological diversity requires managers to first recognize the primary conservation targets and their sensitivity to change (M Hagerman & MA Chan, 2009). Climate exerts a disproportionate control over some species, ecosystems and ecological processes. Those exhibiting a high degree of specialization, for example, surviving at extremes, or with limited dispersal or evolutionary capacity, can be considered particularly sensitive. With future projections indicating that climate-change impacts will be increasingly unevenly distributed in space and time, equating sensitivity to exposure provides a sound basis for evaluating relative vulnerability and risk. Put simply, the greater the sensitivity and exposure, the greater the risk.

Four commonly proposed adaptation strategies are applicable in the conservation context. The first three seek to reduce extinction risk primarily by addressing the effects of climate change on species distributions and by passively influencing mediating drivers. The last considers a more interventionist option. Managing the matrix as a buffer should protect core populations and facilitate shifts across landscapes. New and dynamic reserves primarily protect core populations and accommodate targeted movement.

Community-Based Approaches

Local-level adaptation is widely acknowledged as an important complement to national and global efforts. Community-based approaches therefore constitute an integral part of the overall response framework. Participatory methods provide a means for communities to visualize and affectively engage with their climatically

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challenged futures. They enable informed decisions at the household level, strengthening adaptive capacity through a deeper contextual understanding of climate dynamics (Gidley et al., 2009). Indigenous knowledge is already employed in water resource management, agriculture, and the integrated management of natural ecosystems.

1. Engaging Local Communities

Understanding local adaptation and mitigation is fundamental to effective climate change policy. Complementary local and traditional knowledge enables community governance of resources and adaptation to ecological changes. In-situ people can observe and respond to climate fluctuations, providing local-level information on environmental drivers and stressors relevant to adaptation (Keeley, 2012). Adaptive practices may incorporate both indigenous and Western knowledge, creating hybrid systems attuned to local circumstances rather than generalized frameworks. Successful community-based adaptation builds resilience for societal, economic, and ecological systems.

Community-based adaptation is a key approach within community-based resource management. It combines local, indigenous, and scientific knowledge applied through participatory and advocacy planning processes to address contemporary climate impacts on social-ecological systems. Such strategies encourage engagement of marginalized groups, horizontal learning networks, and intergenerational knowledge transfer, complementing other adaptation strategies at continental, national, and regional scales. Aligning with Principles 2 and 3 of Framework for Adaptation Strategies, community-based approaches distribute adaptation responsibilities more equitably within and among communities, empowering those most vulnerable. Engaging local populations early in the adaptation process fosters more locally appropriate, sustainable solutions.

2. Indigenous Knowledge and Practices

The adaptive capacities of indigenous communities have received increasing recognition from scientists and policymakers. Despite their considerable vulnerability to climate change, these groups display innovative strategies to cope with associated uncertainties—strategies whose effectiveness can be enhanced with suitable support.

The concepts of indigenous knowledge and traditional knowledge have been invoked to designate the local and often tacit bodies of knowledge that indigenous peoples have accumulated over many generations. This knowledge is applied on a continuing basis to sustain the needs of their members. More specifically, the expression indigenous knowledge of climate (IKC) relates to a wide and varied knowledge base comprising local observations, experiences and understandings of climate—and of related biophysical and social factors—which provide an empirical base for decision-making and adaptation to climatic conditions (D. Santha et al., 2010).

Indigenous groups have developed and deployed a vast array of strategies to anticipate and respond to climate threats and impacts. These strategies include exemplars widely adopted in climate-change adaptation, such as water-harvesting techniques, use of drought-resistant crops, coastal stabilization, intercropping, contact with other populations, and integrated strategies for natural resources management and livelihood diversification. However, the adaptive potential of indigenous strategies extends beyond the strictly technical dimension to encompass the institutions, networks and beliefs through which they are transmitted and implemented, which support long-term resilience. Scaling up indigenous adaptive strategies therefore entails embracing the diversity, social and geographical specificity of indigenous cultures, and investing in a combination of complementary learning-, innovation- and transformation-driven pathways towards a resilient future.

Policy and Governance

National-level policy guidance and a common global framework are indispensable for directing effective climate change adaptation (Ruhl, 2010). Several stage-setting instruments are already in place or under negotiation, including the Cancun Adaptation Framework under the United Nations Framework Convention on Climate Change (UNFCCC), National Adaptation Plans (NAPs), and National Adaptation Programmes of Action (NAPAs). Tools such as the Adaptation Policy Framework (APF) and the Economics of Adaptation to Climate Change Support Tool (EACC) are also widely used, supporting an expanded set of development-focused assessment tools. Under the Framework Convention on Climate Change (FCCC), several National Communications have included adaptation components, providing early insights into adaptation measures. Ongoing negotiations under the UNFCCC, particularly related to the terms of reference for National Adaptation Plans, Impacts, Vulnerability and Adaptation initiatives, and the Warsaw International Mechanism on Loss and Damage, are expected to further influence national policy and planning. Governance models that incorporate community interaction and experimentation with emerging policies can strengthen mechanisms for implementing adaptation measures. Once policies are fully established, the significant challenge will be to design and apply the necessary governance structures at local and national levels (Tanner et al., 2019).

1. National Adaptation Policies

The drafting of national adaptation policies involves multiple steps, beginning with a stocktaking of historical climate trends, current and projected hazards, and vulnerability patterns. This provides a robust pre-assessment to inform policy formulation and ensures the effective mobilisation and targeting of climate finance towards the most vulnerable sectors and groups. The initial articulation of the policy sets the foundation by describing the policy context at national, regional, and international levels; institutional responsibilities; and other relevant laws and policies. A comprehensive vulnerability and adaptation assessment follows, serving as the core analytical input that identifies priority sectors for intervention and policy objectives. Following this, a detailed assessment of policy

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options and available climate information supports the formulation of strategic, operational, and cross-cutting policy measures. The subsequent drafting of the policy document includes an implementation and monitoring framework with specific guidelines, indicators, and targets. Finally, extensive consultation with the government and national stakeholders ensures alignment with national development priorities, consensus-building, and political commitment, thereby facilitating smooth adoption and implementation.

2. International Frameworks and Agreements

Conflicts and synergies between adaptation strategies are unavoidable in multi-objective adaptation (Papadimitriou et al., 2019). Reducing impacts via adaptation requires action that is integrated across sectors and scales to prevent the exploitation of water and land resources being exceeded. To reinforce the links between climate actions and sustainable development, adaptation responses should be aligned with the goals of environmental conservation, economic development and social wellbeing without compromising equity and effectiveness. Supporting investment in adaptation and resilience building is essential to avoid "lock-in" to pathways that will further increase vulnerabilities.

The Paris Agreement, adopted in 2015, has played an important role in extending the international climate change framework beyond mitigation to include adaptation as an explicit global aim, advancing the global effort to build climate resilience. As a global framework, it has provided the impetus for national goals and strategies to be developed. Distinct from the United Nations Framework Convention on Climate Change (UNFCCC), the Paris Agreement is an agenda for action that sets out an enhancement of international efforts to limit greenhouse-gas emissions and, at the same time, sets out a comprehensive new foundation for reducing climate risks, through both mitigation and adaptation frameworks. Its dual aim of reducing both the risk of climate change itself, through mitigation, and the risks arising from climate change, through adaptation, responds to the expectations of policy-makers in many countries. Success rests on effective global implementation, and significant challenges remain over how to interpret national adaptation needs within global frameworks.

The 2010 Cancun Agreements under the UNFCCC identified four priorities for effective adaptation that provide a basis for national adaptation goals but do not constrain individual country interpretations. These priorities cover enhancement of national-level adaptation planning, means of implementation, economic diversification and transformational approaches. They offer an opportunity to embed accessible funding mechanisms, knowledge transfer, capacity-building and technology development within the operational detail of plans and strategies, emerging at a critical stage of the global climate change agenda. Agreements under the UNFCCC that build on the Cancun pillars include:

- Enhance national adaptation policies, strategies and plans, accompanied by monitoring and evaluation frameworks
- Provide adequate and timely support for adaptation planning and implementation
- Promote economic diversification to build greater flexibility for societies and sectors
- Promote transformational approaches to shift socio-economic structures in ways that enable greater resilience

Technology and Innovation

At the heart of climate change adaptation lies technological innovation. New technologies enable locating and assessing climate risks in advance; creating and sharing localized climate forecast models; monitoring environmental parameters and providing actionable information; and facilitating communication amongst affected groups. They transform destructive natural hazards into manageable risks, as exemplified by aftershock forecasting for humanitarian assistance. Climate services enable anticipatory or risk-informed action, a shared pathway across humanitarian, development, and climate adaptation activities. Success also requires supportive finance, sound policy, and shared goals at national and international levels (Hope et al., 2019).

Information and communication technologies (ICTs) occupy a strategic position in this approach. As the 2015 Climate Change Conference to develop a new global agreement highlighted, ICTs—widely acknowledged as major drivers and facilitators of all forms of social and economic development—have the potential to reduce greenhouse gas emissions, thus supporting mitigation efforts. Their deployment enhances greenhouse gas emissions-tracking and management capabilities and bolsters the capacity for both mitigation and adaptation. Empowered by ICTs, developing countries could leapfrog to low-carbon development pathways and implement resilient adaptation strategies much more rapidly than anticipated. In addition to driving emissions economies and improving access to carbon accounting systems, ICTs generate robust disaster early-warning systems and significantly facilitate economic diversification and financial inclusion (Valeria Ospina & Heeks, 2010).

1. Emerging Technologies in Adaptation

Increasing global observations and longer data records have begun to reveal the added value of emerging technologies for adaptation. Early investigations indicated prospects for new adaptive capacity among sugarcane and coffee farmers in São Paulo, Brazil (Warner et al., 2018). Current monitoring and demonstration projects link sensors, storage, and management systems to develop new tools and services for improving operational decisions and planning. In the Netherlands, a water authority for the province of Noord-Holland is developing frameworks for monitoring and valuation of adaptation pathways that enable active planning and timely responses during the design of water storage discharges and pumping regimes (Papadimitriou et al., 2019). State-of-the-art increases in

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Earth Observation and sensor systems have much to offer adaptation planners worldwide.

2. Role of Research and Development

Over centuries, research and development (R&D) has facilitated the creation and diffusion of many ingenious adaptation options to environmental change. A central question revolves around the potential of R&D to provide enhanced capabilities and options for new adaptation pathways and to facilitate their deployment (Karlin et al., 2021). Research continues to contribute to knowledge of the human and environmental trajectories of climate change, the dynamics of the Earth system, the interface between them, and the performance of alternative adaptation options. Among the crucial questions is the degree to which contemporary R&D broadly has the institutions and incentive systems necessary to mobilize its scientific and technological assets to undertake projects on the scale and timetable suggested by the challenge and the extent to which new directions might be necessary. In areas such as health and agriculture, where the development of new strains is crucial, the limitations of existing institutions to mount projects at scale are already evident. This section analyzes the roles of institutions that provide research or that engage in the development, diffusion, and deployment of innovative options in the process of adaptation, highlighting the importance of continuing R&D.

Financing Adaptation Efforts

The costs of adaptation have been estimated at 140 to 300 billion USD per year by 2030 for developing countries alone (Nay, 2022). Reducing linear barriers and constraints to public investment that is often underestimated helps to release finance and scale up adaptation solutions (Change Program, 2018). Developed countries have a surplus of savings seeking good investment opportunities and sound projects. Public-private partnerships and blended finance can be pursued to increase investment at scale when private investments alone cannot meet development needs. Several countries include an enhanced role of the private sector and the promotion of climate-resilient investment in their national adaptation plans.

1. Investment Strategies

Granting access to climate-resilient infrastructure and services is essential for adaptation. Yet the United Nations Environment Programme (UNEP) highlights the large gap between adaptation needs and investments. The total global adaptation costs in developing countries are estimated to be $160–$200 billion per year for the period 2020–2030 (at 2010 prices). Scaling up private and public investment for the transition to resilient and low-carbon societies requires huge investment. The expected impacts of climate change create an additional need for investment in resilience and adaptation. These impacts also create an opportunity for investment in resilient systems and services through green recovery strategies. The public sector needs to play a key role by addressing these issues through policies, regulations, guidelines, transparency, and by creating an enabling environment for investments.

Reflecting the cross-cutting nature of climate adaptation challenges, a vast array of financing sources exists. These range from international funds (mainly off budget), to public financing for local development projects, on-budget foreign contributions, or private financing flowing through capital markets. The sizable involvement of different public and private actors illustrates the global scope and complexity of climate change adaptation. Normative and administrative guidelines for project financing, capital transfers, and private participation in developing and emerging economies should be updated to ensure rapid deployment of resources. Capital market liquidity must be increased to facilitate both mitigation and adaptation, taking the particular challenges of adaptation into account. Scalebacked institutions could contribute to market stabilisation, by providing price signals to investors and promoting infrastructure investments in high-risk sectors and regions.

2. Public-Private Partnerships

The pivotal role of public–private partnerships (PPPs) in climate change adaptation originates from their unique capacity to combine the innovative drive and resources of the private sector with the regulatory and coordinating functions of public authorities. Developing bankable adaptation projects capable of attracting private sector financing thus constitutes a major thrust for PPPs. Addressing gaps in defining return rates for adaptation and interpreting benefits through investment community conventions remains an ongoing priority. Climate risk insurance emerges as a more immediate opportunity to meet adaptation goals: 38 countries reference it in their nationally determined contributions (NDCs) and four in their national adaptation plans (NAPs). Bilateral and multilateral initiatives can broaden impact through increased support, improved accountability, and institutionalization of a global partnership on climate risk insurance. Fully operationalizing the Risk Transfer Clearing House as the central resource for climate risk insurance also deserves emphasis.

A Framework for Private Sector Action on Climate Resilience, developed by Business for Social Responsibility, aims to assess climate risks within companies, supply chains, and communities while incorporating the social dimensions of climate change. B Corporations in Latin America have already built resilience to climate change by fostering environmental sustainability and public goods through the constructive leveraging of private sector capabilities. An enabling policy environment has the potential to unlock private sector creativity by promoting access to climate finance, enhancing knowledge generation through climate data and risk assessments, and facilitating innovation through research and development.

PPPs have yet to secure a systematic role in the planning and implementation of adaptation measures in most contexts. However, the emergence of specific climate finance mechanisms and channels opens new opportunities for the mobilization of private sector funds. Investment decisions on a broader scale could be influenced by integrating climate change risks and resilience into existing public–private

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development and financing partnerships and frameworks (Change Program, 2018).

Monitoring and Evaluation

The development of climate change adaptation is an iterative learning process; it requires guidance on whether objectives have been reached and whether to reinforce, scale, or change direction. Many barriers and limits to adaptation exist, and providing insight into the success of efforts can help address these challenges (Klostermann et al., 2018). Adaptation therefore needs continuous monitoring and evaluation (M&E) to determine if actions meet changing risks and if efforts enhance resilience and sustainability.

Effective M&E contributes to accountability, transparency, and learning. It can demonstrate the extent to which adaptation reduces climate impact and addresses vulnerability, which is particularly important for at-risk or resource-poor groups, as well as lessons for future development pathways. M&E also supports the identification of emerging risks, which is vital when dealing with increasing uncertainty. These challenges require an approach that is flexible and forward looking rather than rigid and backward looking.

A common framework for M&E consists of four components: clarifying the system of interest, selecting indicators, identifying responsible organizations, and establishing procedures. These components systematically guide the description of the system, the process of indicator selection, and the design of monitoring activities, all of which should be reviewed iteratively. The 'system of interest' defines the elements of the physical and social context to be monitored, often derived from the adaptation strategy. The concepts of impacts, vulnerability, resilience, and adaptive capacity describe the adaptation context, incorporating information on exposure, sensitivity, impacts, and capacity, along with relevant socio-political and climatic factors.

1. Assessment of Adaptation Measures

The concept of adaptation, as the adjustment of natural or human systems to actual or expected climatic stimuli or their effects, has repeatedly been emphasized by the IPCC as a necessary component of climate change responses along with mitigation. Given the challenges associated with achieving the global warming target of well below 2 °C, and the associated heterogeneous cooling from a global temperature overshoot, adaptation remains of central importance in the climate change discourse. Adaptation investments diminished during the global financial crisis and are typically less than one-tenth of mitigation investments.

Despite the long-recognized need for adaptation, implementation remains limited even with substantial investments in adaptation science. Dynamic adaptive pathways planning from the Netherlands provides a framework based on the idea that adaptation takes place over time in an increasingly non-stationary, uncertain, and evolving risk landscape. It therefore specifies sequences of incremental adaptation strategies to reduce vulnerability over time while maintaining the flexibility to make later changes to more transformational strategies should this become necessary. Adaptation pathways have been adopted in flood risk management in the UK and the Netherlands, and are generally seen as a useful approach to support decision-making under uncertainty. More flexible adaptation strategies are nonetheless still rarely implemented in practice (Bloemen et al., 2017).

In the absence of flexible strategies, current approaches necessarily involve trade-offs. These are often difficult to avoid in adaptation as objectives spanning different dimensions of society, the economy and the environment can be widely divergent. Across Europe, assessment of the relative performance of different adaptation measures across four criteria has shown many strong trade-offs between economic and social objectives. Given even the most ambitious Paris ambition still does not substantially offset the impacts of climate change already locked into the system, the presence of residual climate and socio-economic impacts after adaptation emphasizes the continued importance of mitigation and of early action (Papadimitriou et al., 2019).

2. Indicators of Success

Adaptation increased resilience to climate change states and reduced the number of SDIs that are negatively affected by climate change, adaptation and their combination. A multi-indicator approach identified "adaptation winners" and "adaptation losers" among SDIs. Trade-offs between SDIs mean that adaptation strategies focused on a limited number of SDIs risk leading to net negative climate change consequences, highlighting the importance of multi-objective adaptation and sustainable development as a pathway to climate-resilient futures. The selection of indicators is scenario dependent, so the diversification of scenarios and the identification of indicators that represent diverse policy agendas is vital for capturing potential outcomes. A cross-sectoral approach improved the understanding of complex synergies and trade-offs between adaptation, sectors and regions, information that is essential to support climate-resilient development. Indicators that represent sustainable development agendas help with the identification of unintended consequences and support the design of balanced adaptation policies that reduce the potential for maladaptation; adaptation strategies that are consistent with principles of sustainable development have limited trade-offs and provide synergetic co-benefits (Papadimitriou et al., 2019).

An effective response to climate change requires the creation of societal conditions that support adaptation. Vulnerability depends on both exposure and adaptation capacity. The effectiveness of adaptation depends on the level of mitigation achievable globally in addition to the level of effort at local, regional and national levels. Hence, mitigation and adaptation strategies are intimately linked. Scaling up adaptation planning alongside parallel efforts to reduce greenhouse gases is the basis for sustainability. Adaptation provides a pathway to sustainable development.

Indicators provide an effective means of monitoring the state of the climate system and its dynamics,

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society's exposure and vulnerability to climate change and its impacts tailored to a particular sector or stressor, and the effectiveness of adaptation measures. Where possible, open access and open source databases can improve transparency and cross-comparisons across models and scenarios, and also help with inter-sectoral coordination. Additional work is required to better characterize indices for compound extreme events and for cascading impacts. The development of indicators for the effectiveness of climate change adaptation addresses a pervasive challenge within the field whereby progress is difficult to determine using traditional analytical and sector-specific methodologies. Effective forward-looking adaptation indicators should suggest transformational pathways, be co-designed with stakeholders, be pragmatic and actionable, and not be based solely on the success or failure of past policies or observed impacts (Papadimitriou et al., 2019). Indicators should be multi-level, incorporate socio-economic and climatic factors, and support whole-of-government decision-making.

Case Studies

Illustrations of effective climate change adaptation initiatives and shortcomings provide concrete guidance for program development. A three-year regional project, centered in Vermont and inclusive of New Hampshire, Massachusetts, and New York, engaged two dozen coastal organizations through interviews and participatory workshops to distill lessons from community experiences, needs, and attitudes. Initial analyses identified challenges associated with limited time, information, and resources; yet repeated measures ensured community participation remained uninterrupted (Keeley, 2012). Climate displacement emerges as a prevalent theme in case studies of climate-forced displacement and migration following disasters, catastrophic events, and climate-related crises and conflicts. Both internal and international migration were often compelled by sudden-onset disaster after-effects, whereas protracted hazardous events, environmental degradation, and chronic water and food scarcity tended to initiate local, internal population outflows accompanied by displacements and relocations. In several examples, climate migrants left largely because of a loss of income or failed livelihoods, encountered hardships in transit, poverty and marginality in receiving environments, and, in those cases where the original drivers were not adequately addressed, protracted displacement (Warner et al., 2018).

A regional study of flood-risk-management adaptation strategies reveals that such strategies often oscillate between incremental and transformational modalities. The National Research Council, for instance, highlights the non-fixed character of flexible adaptation pathways, advocating for periodic reevaluation of adaptive measures according to evolving risk thresholds. Incremental approaches emphasize small-scale interventions attuned to predictable change patterns, while transformational strategies entail radical system alterations designed to confront severe or abrupt perturbations. Currently, many sectors adhere to established best practices, predominantly incremental, but the prospect of asset protection, sectoral overhaul, retreat, and systemic transition becomes increasingly salient over extended horizons. Although transformation eventually supersedes incrementalism in adaptation measures, guidance for effecting this transition remains underdeveloped. Prior to critical events such as Hurricane Sandy, strategic emphasis centered on disruption avoidance, with sustained transformation presenting a persistent challenge. Consequently, adaptive pathways occupy a focal role in facilitating transformative action. Recognition of adaptation imperatives is widespread; conversely, implementation lags significantly, despite substantial investment. The application of adaptive pathways has been examined in contexts such as the United Kingdom and the Netherlands and juxtaposed against broader methodological discourse (Bloemen et al., 2017).

1. Successful Adaptation Initiatives

Examples of successful adaptation initiatives illustrate ways in which societies can increase their resilience to climate change. Adaptation implemented locally and through the bottom-up engagement of networks appears to offer the greatest potential for rapid response, enabling methods to be distributed broadly among sites exposed to similar climate risks (Shan, 2018). Projects sensitive to the needs of indigenous groups institute practices that comply with local legislation and accord with global human rights standards (Warner et al., 2018). Institutional actors using formal adaptive governance mechanisms mitigate risks related to social equity and promote environmental sustainability and long-term social–ecological resilience.

Investments made with climate adaptation goals in mind constitute a significant step forward, though the potential path dependency created by mining-related infrastructure development has yet to be fully considered alongside assessments of long-term climate suitability. Partial adaptation measures guided largely by technical criteria and applied without systematic and comprehensive consideration of the systems in which they are embedded can exacerbate existing risks (Papadimitriou et al., 2019). In cases where decision-making processes were divorced from the resource systems in question, conflicts increased between sites and sectors, and risks related to the governance of several resources multiplied—in some cases with catastrophic results.

2. Lessons Learned from Failures

Even well-planned and well-financed projects may fail because of unforeseen shifts in climate, resources, population, or markets. Yet the failure of existing projects can provide valuable information about what is not sustainable or conditions for success. Failures occur at all scales and in most sectors. Taiwan's vital hydroelectric power development in the mid-1970s covaried with a drought period and decline in reservoir levels that was not anticipated in the reservoir model, thereby limiting power production. The Three Gorges Dam in China continues to be mired in controversy, with residents displaced, inadequate budgets, and fears over structural safety. Urban expansions in cities such as New York and London have increased vulnerability to floods at several scales after the

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installations are complete. In the Amazon region, an integrated analysis has shown that infrastructure investments designed to boost economic activity there may instead undermine both economic development and the environment.

Although many of these problems arise from poor planning, co-development of infrastructure and settlements, or inadequate evaluation of ecological feedbacks, some represent a lack of flexibility in the system itself. This means that improved planning alone may not be sufficient. Instead, alternative pathways should be explored that ensure a robust and sustainable society, such as the strategies put forth for New York City in anticipation of future sea-level rise and flooding. These collective experiences highlight the necessity for resilience and sustainability to be explicit goals in the design of climate change adaptations.

Future Directions

Monitoring, evaluation, and learning are crucial throughout the adaptive-management process. Adaptive-management strategies for adaptation must be flexible, entail an iterative learning process, and be capable of responding to new climate-change information and information on the effectiveness of adaptation measures. Such strategies ensure that appropriate actions are undertaken and that unnecessary and maladaptive responses are avoided.

Climate change and its consequences will continue to present new challenges; adaptive capacity and resilience will therefore need to be maintained, enhanced, and monitored. Potential threats and vulnerabilities related to climate change are continually evolving. For example, extreme events are growing in frequency and severity, and the emergence of new diseases or pests in some locations can be expected. Emergent issues—such as changes in net-present-day water requirements, in necessary discharge levels, or in inundation levels—may also arise if new evidence significantly revises earlier assessments of climate change (Muntasir, 2017). Challenges and opportunities for innovation will remain. Certain issues—such as forward-looking decisions about preferred settlement locations or investment thresholds for protective infrastructure—are not currently informed by scientific evidence or climate predictions at the relevant resolution. Specific uncertainties that are relevant to particular decisions, locations, or sectors may furthermore persist.

1. Emerging Challenges

The global community is at a crossroads on the issue of climate change. Neither mitigation nor adaptation emerged as a solution under traditional economic analysis. The long-term value of mitigation was too uncertain and the costs perceived as too high. Adaptation was excluded from analysis with claims that costs were unknowable, and if climate change were bad, numerous adaptations would be attempted and the problem ignored. The state of the world entering the 2010 Conference of Parties in Copenhagen was that common sense prevailed and an innovative text put on the table to break the impasse. The recognition that climate change had a real and damaging impact transformed the ideas around both mitigation and adaptation. A global programme of work was mapped out to the approval of all parties. Critical to the success of the programme was the recognition that the economic analysis of climate change had missed key points on both fronts. Successful responses to climate change mitigation would require a set of development cofactors — technology, investment, existential risk, capability to make choices — that were largely absent in the present analysis. Attributes that have made development very challenging in many areas of the world at many times in history. More fundamentally, none of these characteristics was likely to become widespread without a concerted and immediate commitment to universal development goals. Successful adaptation had also been prematurely ruled as not feasible. Adaptation and development are distinct concepts and change would bring about a range of negative consequences, some of which could not be adapted to. However, the flexibility that humans and ecosystems possess implies a capacity to accommodate large impacts and adapt to changes, if not necessarily to the changes envisaged under a business-as-usual policy framework (S. Colgan et al., 2016).

A central challenge facing humanity is to devise effective climate policies against a backdrop of high uncertainty and inevitable surprises. Neither a prediction nor observations of the present climate can provide robust criteria by which to choose among the diverse policy options. A large and positive framing of the question that allows waiving these problems and thus guides the undertaking is: “How can society adapt to the range of changes implied by the full spectrum of climate change scenarios and still preserve our well-being?” Adaptation is fundamental to this approach and a rich body of natural and social science serves as a guide to fulfilling these goals. Knowledge exists on the vulnerability of a range of natural and social systems, the ways in which we adapt to gradually changing environments, social learning, and important precursors to successful adaptation. Additionally, the limits to the scope of adaptation and the forms of climate change where adaptation fails are known.

2. Opportunities for Innovation

Good adaptation options can make a substantial contribution to many development and humanitarian goals. However, choosing between broadly defined adaptation actions is challenging because (a) there are many targets for adaptation, which collectively may not all be achievable; (b) multiple mechanisms link climate factors to development goals, producing divergent system responses; (c) there are competing conservation and development priorities; and (d) global change upends spatial and temporal patterns of temperature, water stress, productivity and disease. These factors hinder the identification of opportunities for innovation. Innovation is closely related to adaptation because it opens new avenues to meeting humanitarian and development goals. Yet many dominant pathways are incremental, not transformative, despite the scope of the challenges that are faced. Guidance on innovation pathways

would help to identify where and when more radical strategies may be warranted.

Adaptation options have different effects on multiple targets and different synergies and trade-offs with development objectives. Future adaptation effort built on the current portfolio will be insufficient. Even with unconstrained investment, it will be very difficult to avoid hard and potentially very disruptive trade-offs. Early action, international cooperation and societal transformation will be needed to deliver positive outcomes across multiple objectives. Adaptation losses (i.e. gaps between planning targets and achievable objectives) are not just a result of high-end climate change or pessimistic socio-economic futures. They arise even for low climate change scenarios and expansive socio-economic futures (Papadimitriou et al., 2019).

Pathways from innovation to humanitarian and development goals vary greatly and involve many mechanisms, not just technology. Research has focused on either innovation to boost adaptive capacity, often within a linear supply-push framework, or on categorizing incremental versus transformative adaptation at the exposition-demand level. However, it fails to examine the content of innovation, the dynamics of development processes, or the micro-level interactions beginning innovation activity. These are vital for assessing whether innovation is likely to be incremental or transformative. Carefully attended interactions between exogenous and endogenous factors determine the innovation pathway and the kind of change likely to be encountered at the development or humanitarian level (Hope et al., 2019).

Conclusion

Adaptation is essential for humanity to sustain a stable and desirable future in response to global climate change. The variety of adaptation responses that can reduce climate risk is diverse and highly location- and context-specific. Recent work has developed numerous adaptation pathways that can provide integrated and transformational strategies for climate-resilient development. The pathway concept describes sequences of possible systems or modes of responses to changing external drivers. It offers a coherent approach for formulating long-term adaptation options and mixed portfolios of adaptive actions, thereby linking tactical decisions with long-term strategy. It also facilitates consideration of thresholds, trade-offs, and complex adaptive management initiatives within a common framework. Although limited application experience warrants the exploration of major open research questions, recent developments mark this approach as a promising and active research frontier for sustainable climate adaptation (Bloemen et al., 2017).

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