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Insight: Social-Ecological Resilience of Systems: Towards Sustainability

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Abstract

Social-ecological resilience has become a cornerstone of sustainability science, offering a framework for understanding how coupled human-environment systems absorb disturbances, adapt to changing conditions, and transform while maintaining essential functions. This paper explores resilience as a set of pillars for climate action and governance, focusing on biodiversity, reversibility, social action capacity, and ecological footprint. Drawing on structuration theory, resilience scholarship, and recent IPCC reports on climate change and cities, it develops a conceptual framework that emphasizes cross-pillar synergies, mitigation linkages, and operationalization pathways. Case examples from Colombia, Peru, and Kenya illustrate how existing instruments can advance these pillars and how new approaches can strengthen them. The paper concludes that resilience is both an ecological and social property, requiring governance instruments, planning tools, and cultural shifts to embed these pillars into systemic design for sustainability, while harmonizing adaptation and mitigation within national climate strategies and NDC frameworks.

1. Introduction

The accelerating pace of global change has placed unprecedented stress on both ecological and social systems. Climate change, biodiversity loss, urban expansion, and economic globalization are reshaping the conditions under which societies and ecosystems interact. In this context, resilience has become a critical concept for sustainability. Resilience is not simply the ability to withstand shocks; it is the capacity to adapt and transform while maintaining essential functions. Understanding resilience requires examining the dynamic interplay between ecological processes and social structures, recognizing that neither can exist independently of the other.

Social-ecological systems are complex and adaptive, characterized by feedback loops, thresholds, and co-evolutionary dynamics. They are shaped by both biophysical processes and social institutions, and their resilience depends on the interactions between these dimensions. As Gunderson (2003) and Holling (2000) argue, resilience is a property that emerges from systemic interactions across scales, rather than a static attribute. It is therefore essential to conceptualize resilience in ways that integrate ecological and social dimensions, moving beyond reductionist approaches that treat them separately.

Urbanization exemplifies the challenges of resilience. Urban centers concentrate populations and resources, generating stressors that transcend local boundaries and influence distant ecosystems. They deplete local ecosystem services, increase dependence on external resources, and raise the cost of providing social services. Yet urban centers also have the potential to innovate, redesign human activities, and foster resilience through sustainable planning, technology, and governance. The restoration and conservation of local ecosystems become imperative to ensure that resilience is not lost.

This paper develops a conceptual framework for social-ecological resilience, drawing on structuration theory, resilience scholarship, and IPCC assessments of climate change and cities. It explores resilience as a set of pillars — biodiversity, reversibility, social action capacity, and ecological footprint — and emphasizes cross-pillar synergies, mitigation linkages, and operationalization pathways. The framework is then applied to case examples from Colombia, Peru, and Kenya, illustrating how resilience can be integrated into climate governance and urban planning. The paper concludes that resilience is both an ecological and social property, requiring integrated approaches that harmonize adaptation and mitigation within national climate strategies and NDC frameworks.

2. Conceptual Framework: Socio-Ecological Resilience

Socio-ecological resilience is best understood as a systemic property that emerges from the interactions between ecological processes and social structures. It is not a fixed state but a dynamic capacity shaped by feedback loops, thresholds, and co-evolutionary dynamics. As Holling (2000) emphasizes, resilience involves the ability of systems to absorb disturbances, reorganize, and continue functioning. This capacity depends on both ecological attributes, such as biodiversity, and social attributes, such as governance and cultural values.

Structuration theory provides a useful lens for analyzing the social dimensions of resilience. Giddens (1987) identifies three dimensions of structure — signification, domination, and legitimation — and three dimensions of interaction — communication, power, and sanction. These dimensions shape the distribution of resources, the exercise of authority, and the legitimacy of institutions. When applied to socio-ecological systems, structuration theory highlights how social structures enable or constrain ecological resilience. Governance arrangements, for example, can either mitigate stressors by promoting sustainable land use and waste management, or exacerbate them by incentivizing unsustainable practices.

Resilience can be conceptualized through four interconnected pillars that provide direction for climate action and governance**. The first pillar is ecological biodiversity**, which reflects the diversity of land types, habitats, and species richness. Biodiversity is not only a foundation for adaptation but also a contributor to mitigation, since conserving and restoring ecosystems enhances carbon sequestration and storage. **The second pillar is reversibility**, which indicates the likelihood that disturbed ecosystems can return to a healthier state. Restoration of degraded lands contributes directly to mitigation by reducing emissions from deforestation and land-use change, while also enhancing adaptive capacity by rebuilding ecological thresholds. **The third pillar is social action capacity**, which assesses the ability of societies to mitigate stressors through governance, social learning, and collective action. Social action capacity is essential for ensuring that mitigation policies are socially viable and equitable, while also enabling communities to adapt to climate impacts. **The fourth pillar is the ecological footprint**, which estimates local carrying capacity and indicates the level of substitution from direct access to ecosystem services to indirect access through urban social services. Reducing ecological footprints contributes to mitigation by lowering emissions from production, consumption, and waste, while also strengthening adaptation by reducing dependence on distant ecosystems.

These four pillars are not isolated; they reinforce one another through systemic feedbacks. Biodiversity enhances reversibility, as diverse ecosystems recover more quickly from disturbances, while reversibility supports biodiversity by restoring habitats that sustain species' richness. Social action capacity reduces ecological footprints, as informed and empowered communities adopt sustainable practices, while lower ecological footprints protect biodiversity by reducing pressure on ecosystems. These synergies highlight resilience as a systemic property: progress in one pillar strengthens others, creating virtuous cycles of sustainability.

A critical refinement of the framework is its explicit linkage to both mitigation and adaptation. While NDCs are often mitigation-focused, resilience pillars demonstrate dual benefits. Biodiversity and reversibility reduce emissions while enhancing adaptive capacity. Social action capacity ensures that mitigation policies are equitable and politically viable. Ecological footprint reduction aligns consumption with emissions reduction and adaptation goals. By embedding resilience pillars into NDCs as dual-purpose instruments, countries can harmonize local adaptation initiatives with national mitigation commitments, ensuring coherence across scales.

To move from concept to practice, resilience pillars must be embedded into governance instruments and planning processes. At the national level, resilience indicators should be integrated into NDC monitoring frameworks, ensuring that biodiversity, reversibility, social action, and ecological footprints are tracked alongside emissions reductions. At the municipal level, local budgets and land-use plans must be aligned with national climate strategies, embedding nature-based solutions, restoration programs, participatory governance, and footprint assessments into urban planning. Across scales, adaptation and mitigation must be treated as complementary domains, using instruments such as ecosystem-based adaptation, circular economy strategies, and participatory governance to simultaneously reduce emissions and build resilience.

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Resilience can be conceptualized through four interconnected pillars that provide direction for climate action and governance. The first pillar is ecological biodiversity, which reflects the diversity of land types, habitats, and species richness. High biodiversity increases the likelihood of favorable interactions and functions that can react to stressors. Ecosystem services, including water purification, nutrient cycling, and energy transfer, are derived from ecological stocks such as wetlands, soil, air, vegetation, and water (Hamann, Biggs, & Reyers, 2015; Maseyk et al., 2017). Biodiversity is not only an adaptation resource but also a mitigation instrument, since conserving and restoring ecosystems enhances carbon sequestration and storage. Operationally, biodiversity can be embedded into urban planning through ecological zoning, green corridors, and nature-based solutions that simultaneously reduce emissions and buffer communities against climate impacts.

The second pillar is reversibility, which indicates the likelihood that disturbed ecosystems can return to a healthier state. Reversibility depends on the fraction of land susceptible to erosion, the conservation land lost to urban expansion, and the remaining conservation land that provides ecological benefits such as aquifer recharge, species preservation, soil erosion reduction, and carbon sequestration (Rodríguez et al., 2006). Restoration of degraded lands contributes directly to mitigation by reducing emissions from deforestation and land-use change, while also enhancing adaptive capacity by rebuilding ecological thresholds. Operationalization of reversibility requires watershed restoration programs, reforestation initiatives, ecological zoning, and payment for ecosystem services schemes that are integrated into municipal budgets and linked to national climate strategies.

The third pillar is social action capacity, which assesses the ability of societies to mitigate stressors through governance, social learning, and collective action. As Liu et al. (2007) illustrate, strong governance and social learning can reverse environmental damage and restore key ecological resources. Social action capacity is essential for ensuring that mitigation policies are socially viable and equitable, while also enabling communities to adapt to climate impacts. Operationalization involves participatory climate budgeting, climate education programs, and community-based adaptation strategies embedded in municipal planning. By embedding social action capacity into NDC implementation frameworks, countries can ensure that mitigation and adaptation policies are coherent, inclusive, and politically sustainable.

The fourth pillar is the ecological footprint, which estimates local carrying capacity and indicates the level of substitution from direct access to ecosystem services to indirect access through urban social services. A high footprint signifies that local and neighboring ecological resources are being depleted, reflecting poor governance and/or overpopulation (Suárez et al., 2016; Rees & Wackernagel, 2008). Reducing ecological footprints contributes to mitigation by lowering emissions from production, consumption, and waste, while also strengthening adaptation by reducing dependence on distant ecosystems. Operationalization requires sustainable transport policies, waste management reforms, and integration of footprint assessments into metropolitan land-use plans, ensuring that urban development remains within ecological limits.

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This expanded conceptual framework demonstrates that socio-ecological resilience is both an ecological and social property, requiring integrated approaches that embed biodiversity, reversibility, social action capacity, and ecological footprint into climate governance and urban planning. By emphasizing cross-pillar synergies, mitigation linkages, and operationalization pathways, the framework provides a robust and actionable foundation for advancing sustainability in socio-ecological systems**.**

4. Integrating Resilience Pillars into Climate Governance and Urban Planning

4.1 Biodiversity

In **Colombia**, biodiversity is integrated into planning through ecological zoning, green corridors, and the National Biodiversity Strategy and Action Plan. Bogotá's "Green Belt" program and Medellín's "Green Corridors" initiative link biodiversity protection with air quality improvement and flood mitigation. These local instruments are coherent with Colombia's national climate policy, which emphasizes ecosystem-based adaptation under the Ministry of Environment. However, coherence could be strengthened by harmonizing municipal biodiversity initiatives with national NDC targets, ensuring that local actions contribute to centralized climate narratives.

In **Peru**, Lima's metropolitan planning incorporates wetland protection as natural buffers against flooding, supported by the Ministry of Environment's territorial approach to nature-based solutions. Instruments include the National Wetlands Strategy and integration of Nature-based Solutions (NbS) into the National Adaptation Plan. While these instruments align with Peru's NDC commitments, they remain fragmented across municipal jurisdictions. Strengthening coherence requires integrating biodiversity targets into metropolitan land-use plans and ensuring that NbS are mainstreamed across all levels of governance.

In **Kenya**, biodiversity is integrated into climate risk profiles through the Kenya Urban Support Program and the National Climate Change Action Plan. Instruments include community-based conservation programs and county-level climate risk assessments. These initiatives are coherent with Kenya's decentralized governance model, but harmonization with national narratives could be improved by embedding biodiversity indicators into the monitoring framework of Kenya's NDC.

4.2 Reversibility

Reversibility requires instruments that restore degraded ecosystems and prevent irreversible damage. In **Colombia**, the National Unit for Disaster Risk Management promotes watershed restoration and reforestation as resilience strategies. Instruments such as the National Restoration Plan and payment for ecosystem services schemes support reversibility. These are coherent with Colombia's national climate policy but could be strengthened by integrating restoration targets into municipal budgets and ensuring that local governments have the capacity to implement them.

In **Peru**, projects financed by the Adaptation Fund restore vulnerable ecosystems through reforestation and wetland recovery. Instruments include the National Forest Conservation Program and ecosystem-based adaptation projects in coastal and Andean regions. While coherent with Peru's NDC, reversibility efforts remain project-based and donor-driven. Strengthening coherence requires institutionalizing restoration programs within municipal planning frameworks and linking them to national adaptation targets.

In **Kenya**, counties embed ecosystem restoration into municipal infrastructure delivery, ensuring that new urban projects include ecological buffers. Instruments include the National Forest Program and county-level reforestation initiatives. These are coherent with Kenya's decentralized governance system, but harmonization with national narratives could be improved by embedding restoration indicators into Kenya's NDC monitoring framework.

4.3 Social Action Capacity

Social action capacity depends on governance, participation, and social learning. In **Colombia**, multi-level governance frameworks link national climate policy with municipal planning. Instruments include the *National Climate Change System (SISCLIMA)*, which coordinates climate action across ministries and municipalities, and participatory planning processes in Bogotá and Medellín. These instruments are coherent with Colombia's centralized climate narrative but could be strengthened by embedding participatory governance into NDC implementation frameworks, ensuring that local voices shape national climate commitments.

In **Peru**, community-based adaptation is emphasized in cities vulnerable to El Niño. Instruments include the *National Adaptation Plan*, which integrates social inclusion and poverty reduction into resilience strategies, and municipal participatory budgeting processes. While coherent with Peru's national climate policy, social action capacity could be strengthened by harmonizing community-based adaptation initiatives with national NDC targets, ensuring that local actions contribute to centralized climate narratives.

In **Kenya**, urban governments use the *Urban Climate Risk Profile Preparation Guidelines* developed by the Global Center on Adaptation to build local technical capacity and empower communities. Instruments include county climate change funds and participatory planning processes. These are coherent with Kenya's decentralized governance system, but harmonization with national narratives could be improved by embedding social action indicators into Kenya's NDC monitoring framework.

4.4 Ecological Footprint

Reducing ecological footprints requires instruments that address consumption, waste, and resource dependence. In **Colombia**, urban centers experiment with *circular economy strategies* to reduce waste and resource use, supported by the *National Circular Economy Strategy*. These instruments are coherent with Colombia's national climate policy but could be strengthened by integrating ecological footprint assessments into municipal planning frameworks and linking them to NDC monitoring.

In **Peru**, the Ministry of Environment promotes *sustainable transport* and *waste management policies* in Lima, aiming to reduce the city's ecological footprint. Instruments include the *Nationally Appropriate Mitigation Actions (NAMAs)* for transport and waste, and the *National Climate Change Strategy*. While coherent with Peru's NDC commitments, ecological footprint reduction remains fragmented across sectors. Strengthening coherence requires integrating footprint assessments into metropolitan land-use plans and linking them to national monitoring frameworks.

In **Kenya**, counties embed *resource efficiency standards* into municipal infrastructure projects, supported by the *National Climate Change Action Plan*. Instruments include county climate change funds and sustainable consumption policies. These are coherent with Kenya's decentralized governance system, but harmonization with national narratives could be improved by embedding ecological footprint indicators into Kenya's NDC monitoring framework.

4.5 Synthesis

Across Colombia, Peru, and Kenya, the four pillars of resilience — biodiversity, reversibility, social action capacity, and ecological footprint — are being integrated into climate governance and urban planning through diverse instruments. Yet these instruments often remain fragmented, implemented at municipal or project levels without systematic integration into national climate strategies.

The fragmentation arises because NDCs are primarily mitigation-oriented, focusing on emissions reduction while adaptation and resilience receive less systematic attention. This imbalance creates a gap between local resilience initiatives and national climate narratives. For example, biodiversity corridors in Bogotá or wetland protection in Lima contribute to adaptation but are not explicitly linked to national mitigation targets. Similarly, Kenya's county-level restoration projects strengthen local resilience but are not systematically embedded into national NDC monitoring frameworks.

To build harmonization, resilience pillars must be embedded into NDCs as cross-cutting elements that support both mitigation and adaptation. Biodiversity conservation contributes to carbon sequestration (mitigation) while enhancing ecosystem services that buffer communities against climate impacts (adaptation). Reversibility through restoration programs reduces emissions from degraded lands while strengthening ecological thresholds. Social action capacity ensures that mitigation policies are socially inclusive and politically viable, while ecological footprint reduction aligns consumption patterns with both emissions reduction and adaptation goals. By framing resilience pillars as dual-purpose instruments, NDCs can integrate them into national climate strategies without diluting their mitigation focus.

Strengthening coherence requires three steps. First, resilience indicators should be embedded into NDC monitoring frameworks, ensuring that biodiversity, reversibility, social action, and ecological footprints are tracked alongside emissions reductions. Second, municipal budgets and planning processes must be aligned with national climate strategies, creating vertical integration between local initiatives and centralized narratives. Third, adaptation and mitigation must be treated as complementary rather than separate domains. Instruments such as ecosystem-based adaptation, circular economy strategies, and participatory governance can simultaneously reduce emissions and build resilience, bridging the gap between local action and national commitments.

In sum, while Colombia, Peru, and Kenya have begun integrating resilience pillars into climate governance and urban planning, coherence with national policies and NDCs remains partial. Embedding resilience into NDCs as dual-purpose instruments for mitigation and adaptation offers a pathway to harmonization, ensuring that climate action strengthens both ecological systems and social cohesion.

5. Conclusion

Social-ecological resilience is a critical concept for sustainability. It refers to the capacity of systems to absorb disturbances, adapt to changing conditions, and transform in ways that maintain essential functions. Resilience emerges from the interplay of ecological processes and social structures, and it requires integrated approaches that embed biodiversity, reversibility, social action capacity, and ecological footprint into systemic design.

The challenge lies in avoiding weak sustainability, where natural capital is substituted by manufactured capital, leading to dependence on external ecosystems. Many urban centers already exceed local carrying capacity, relying on distant ecosystems for resources. Resilience requires recognizing the limits of substitution and embedding ecological thresholds into governance arrangements. It also requires cultural shifts that reconnect societies with their environments, fostering social learning and collective action.

Examples from Colombia, Peru, and Kenya show that resilience pillars can be advanced through biodiversity conservation, ecosystem restoration, participatory governance, and sustainable consumption policies. Yet these instruments must be scaled up and integrated into national climate strategies and local urban planning. Embedding resilience into NDCs, municipal budgets, and planning frameworks ensures that climate action is not only about emissions reduction but also about systemic transformation.

In conclusion, resilience is both an ecological and social property. It depends on biodiversity, governance, social learning, reversibility, and ecological footprint. By embedding these pillars into climate governance and urban planning, societies can move beyond adaptation toward transformation, ensuring sustainability in the face of accelerating global change. Resilience is therefore not only a theoretical concept but a practical imperative for sustainability.

Limitations

While this paper develops a conceptual framework for socio-ecological resilience and applies it to case studies in Colombia, Peru, and Kenya, several limitations remain. First, the framework is primarily theoretical and relies on secondary sources; empirical validation through quantitative indicators and longitudinal data would strengthen its applicability. Second, the case studies highlight instruments at national and municipal levels, but they do not fully capture the diversity of local contexts or informal governance arrangements that often shape resilience outcomes. Third, the integration of resilience pillars into NDCs is discussed conceptually, yet the political and institutional challenges of embedding adaptation alongside mitigation are complex and require further exploration. Finally, the framework emphasizes synergies between pillars, but operationalizing these synergies in practice may encounter tradeoffs, resource constraints, and governance fragmentation that were only partially addressed here. These limitations suggest the need for future research that combines comparative empirical studies, participatory approaches, and policy analysis to refine and test the framework in diverse socio-ecological settings.

6. Future Research Directions

Building on the limitations identified, future research should focus on empirically testing and refining the socio-ecological resilience framework across diverse contexts. Comparative case studies that examine how biodiversity, reversibility, social action capacity, and ecological footprint interact in different urban and rural settings would provide valuable insights into cross-pillar synergies and trade-offs. Longitudinal studies could help capture the dynamic nature of resilience; particularly how ecosystems and social systems reorganize after disturbances.

Further research should also explore how resilience pillars can be operationalized within national climate strategies and NDC frameworks. Since NDCs remain largely mitigation-oriented, there is a need to investigate practical mechanisms for embedding adaptation and resilience indicators into monitoring and reporting systems. This includes examining how local initiatives, such as community-based adaptation or municipal restoration programs, can be scaled up and harmonized with centralized narratives.

Another promising direction is the integration of equity and justice dimensions into resilience frameworks. Future studies should assess how resilience policies affect vulnerable populations, and how participatory governance can ensure that adaptation and mitigation strategies are socially inclusive. Finally, interdisciplinary approaches that combine ecological science, social theory, and policy analysis will be essential for advancing resilience as both a theoretical construct and a practical tool for sustainability.

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