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The Carbon–Water–Biodiversity Nexus: A Tri-Dimensional Review of Trade-Offs in Climate Mitigation Policies

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ABSTRACT

Climate mitigation policies are essential for addressing the global challenge of anthropogenic climate change, but their implementation often entails complex interactions with water resources and biodiversity. This narrative review synthesizes recent peer-reviewed literature to explore the carbon–water–biodiversity nexus, emphasizing trade-offs and synergies in mitigation strategies. Traditional climate reviews have typically focused on single metrics, such as carbon emissions reduction, overlooking the interconnected dynamics among carbon sequestration, water security, and biodiversity conservation. By adopting a nexus-based approach, this review highlights how mitigation actions like afforestation, bioenergy with carbon capture and storage (BECCS), and renewable energy deployment can yield co-benefits, such as enhanced ecosystem services, while also posing risks like water scarcity and habitat loss. Drawing on studies from 2019 to 2025, we examine thematic areas including pairwise nexuses (carbon-water, carbon-biodiversity, water-biodiversity) and integrated tri-dimensional perspectives. Key findings reveal that while nature-based solutions offer substantial synergies, poorly designed policies can exacerbate trade-offs, particularly in water-stressed regions or biodiversity hotspots. The review underscores the need for holistic policy frameworks that incorporate nexus thinking to minimize adverse impacts and maximize sustainable outcomes. Objectives include providing a comprehensive synthesis of current evidence, identifying knowledge gaps, and proposing directions for future research to support equitable and effective climate action.

Keywords: *Carbon-water-biodiversity nexus, Climate mitigation policies, Trade-offs and synergies, Nature-based solutions, Ecosystem services, Sustainable development*

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INTRODUCTION

Anthropogenic climate change has emerged as one of the most pressing global challenges of the twenty-first century, driven predominantly by the continuous rise in greenhouse gas emissions from fossil fuel combustion, land-use change, and industrial activities. Among these gases, carbon dioxide (CO2) plays a dominant role due to its high concentration and long atmospheric residence time. As a result, climate mitigation strategies have largely focused on reducing CO2 emissions and enhancing carbon sequestration through technological, ecological, and policy-based interventions. While these measures are essential for limiting global temperature rise in line with international targets, such as those set by the Paris Agreement, their broader environmental implications require careful examination. Climate mitigation efforts do not operate in isolation; rather, they are embedded within complex Earth system processes that directly influence water resources and biological diversity.

Within this context, the carbon–water–biodiversity nexus has emerged as an integrative framework that captures the interdependencies among carbon cycling, hydrological processes, and ecosystem dynamics. This nexus perspective emphasizes that actions aimed at mitigating climate change through carbon management can generate cascading effects—both positive and negative—across water systems and biodiversity components (Baldwin-Cantello *et al.*, 2023). For instance, land-based carbon sequestration initiatives can alter evapotranspiration rates, soil moisture dynamics, and groundwater recharge, while simultaneously reshaping habitats and species composition. Acknowledging these interactions (Johansson & Andersson, 2022; Makhdoom *et al.*, 2022; Bahrawi & Ali, 2023; Rattanakorn & Dhep, 2023; Hakami, 2024; Xie *et al.*, 2024) is critical to preventing unintended consequences that may undermine long-term sustainability goals. The nexus approach therefore moves beyond sector-specific perspectives and supports systems-based thinking for more coherent and resilient climate policy development.

The conceptual foundations of the carbon–water–biodiversity nexus can be traced to earlier integrated resource management frameworks, particularly the water–energy–food nexus, which sought to address competing demands among essential resources. Over time, this framework has expanded to incorporate climate change and biodiversity considerations, reflecting increased recognition that environmental challenges are interconnected rather than isolated. Despite this evolution, many contemporary climate mitigation policies remain largely carbon-centric. Although effective in reducing emissions, such policies may unintentionally affect water availability and ecosystem integrity through land-use changes, altered agricultural practices, and shifts in energy production pathways (Bayer *et al.*, 2023). These interactions underscore the necessity of evaluating mitigation strategies within a broader nexus-based framework.

Empirical studies demonstrate that climate mitigation measures can produce both synergies and trade-offs across the carbon–water–biodiversity nexus. Large-scale afforestation and reforestation projects, widely promoted as nature-based solutions for carbon sequestration, have the potential to enhance biodiversity by restoring degraded landscapes and increasing habitat connectivity. However, in water-limited or arid regions, these interventions may reduce streamflow and water yields due to increased vegetation water consumption, thereby intensifying local and regional water stress (Cohen *et al*., 2021). Similarly, bioenergy production aimed at supporting low-carbon energy transitions can contribute to emission reductions, yet it may also compete with food production for land and water resources and pose risks to endemic species if ecological safeguards are not adequately implemented (Parkinson *et al*., 2019). These examples illustrate that mitigation outcomes are highly context-dependent and require integrated assessment to balance environmental objectives effectively.

Despite a growing body of literature examining pairwise interactions—such as carbon–water or carbon–biodiversity relationships—comprehensive analyses that simultaneously address all three components remain limited. This gap is particularly significant given the increasing emphasis on nature-based solutions in global climate mitigation agendas. By their very nature, such solutions operate at the intersection of carbon sequestration, water regulation, and biodiversity conservation, making them especially sensitive to nexus dynamics (Hirwa *et al*., 2021). A tri-dimensional synthesis is therefore essential to support evidence-based decision-making and to ensure that mitigation strategies deliver multiple co-benefits without exacerbating existing environmental pressures.

The present review addresses this gap by providing a comprehensive examination of the carbon–water–biodiversity nexus in the context of climate mitigation. Drawing exclusively on peer-reviewed journal articles published between 2019 and 2025, the review reflects the most recent scientific developments and policy-relevant insights. The objectives of this review are threefold: (1) to clarify the conceptual framework of the carbon–water–biodiversity nexus and its relevance to climate mitigation efforts; (2) to systematically analyze the synergies and trade-offs associated with key mitigation strategies across terrestrial and aquatic systems; and (3) to highlight integrated approaches and case studies that demonstrate practical applications of nexus-informed planning. By synthesizing current knowledge across disciplines, this article aims to support policymakers, researchers, and practitioners in designing climate mitigation pathways that balance carbon reduction goals with water security and biodiversity conservation.

Conceptual framework of the carbon–water–biodiversity nexus

The carbon–water–biodiversity nexus offers a systemic and integrative framework for analyzing the complex interdependencies among atmospheric carbon management, hydrological processes, and ecological diversity within coupled human–natural systems. At its core, carbon mitigation encompasses processes such as carbon sequestration in terrestrial ecosystems, including soils, forests, wetlands, and agricultural landscapes. These processes are inherently dependent on water availability, as plant productivity, soil microbial activity, and biogeochemical cycling are regulated by hydrological conditions. In turn, changes in carbon management practices can directly and indirectly influence biodiversity by modifying habitat structure, species composition, and ecosystem functioning (Yirdaw *et al*., 2023).

By explicitly incorporating biodiversity as a central component, this framework extends traditional nexus approaches that have historically focused on resource efficiency and trade-offs among carbon, water, and energy. Biodiversity is increasingly recognized not merely as an outcome of environmental management, but as a foundational element that underpins ecosystem resilience, stability, and service provision. Diverse biological communities enhance ecosystem functions such as carbon storage, nutrient cycling, pollination, water regulation, and natural purification processes, thereby strengthening the capacity of ecosystems to respond to climatic and anthropogenic pressures (Samberger, 2022). Integrating biodiversity into the nexus framework thus enables a more comprehensive understanding of how ecosystem integrity mediates carbon–water interactions over spatial and temporal scales.

Within climate mitigation contexts, the carbon–water–biodiversity nexus highlights the cascading effects that may arise when interventions target a single system component. Carbon-centered policies, such as afforestation initiatives or mechanisms like REDD+ (Reducing Emissions from Deforestation and Forest Degradation), illustrate this interconnectedness. While REDD+ programs are designed to reduce emissions and enhance carbon sinks through forest conservation, they also contribute to biodiversity protection by preserving habitats and ecological corridors. At the same time, changes in forest cover and management can alter regional hydrological cycles by affecting evapotranspiration rates, soil moisture retention, and surface runoff patterns, with implications for downstream water availability (Jamion *et al*., 2023). These multidirectional interactions underscore the necessity of evaluating mitigation strategies through an integrated nexus lens rather than through isolated sectoral assessments.

Recent research increasingly emphasizes the importance of quantitative and spatially explicit approaches to capture nexus dynamics. Integrated assessment models, land-use change simulations, and ecosystem service valuation tools are being employed to examine how different mitigation scenarios influence carbon sequestration potential, water resources, and biodiversity outcomes simultaneously. Such models allow researchers to explore future trajectories under alternative policy and management pathways, identify hotspots of synergy or conflict, and assess the sensitivity of nexus interactions to climatic and socioeconomic drivers (Eisenhauer *et al*., 2024). The use of these tools is particularly valuable for informing decision-making under uncertainty, as climate mitigation outcomes often depend on non-linear interactions and context-specific conditions.

The theoretical foundations of the carbon–water–biodiversity nexus are rooted in systems theory and socio-ecological systems thinking, which emphasize feedback mechanisms, thresholds, and emergent properties. Positive feedbacks may arise when high levels of biodiversity enhance ecosystem productivity and carbon storage, for example through complementary resource use in diverse plant communities that increase biomass accumulation and soil carbon inputs. Conversely, negative feedbacks can occur when mitigation strategies intensify pressure on water resources, such as through irrigation-intensive bioenergy crop production, leading to habitat degradation, reduced species richness, and diminished ecosystem services (Paleari, 2024). Recognizing these feedbacks is critical for anticipating unintended consequences and avoiding ecological tipping points.

Equity and social dimensions are also integral to the nexus framework. Trade-offs among carbon, water, and biodiversity are rarely distributed evenly, and their impacts often disproportionately affect vulnerable populations, particularly in regions characterized by high biodiversity value and limited water availability. Indigenous peoples, smallholder farmers, and rural communities frequently depend directly on local ecosystems for livelihoods, food security, and cultural identity. Climate mitigation interventions that fail to account for these dependencies may exacerbate social inequalities and undermine local adaptive capacity (Vargas *et al*., 2023). Incorporating equity considerations into nexus analyses therefore strengthens the legitimacy and effectiveness of mitigation policies.

From a governance perspective, adopting a carbon–water–biodiversity nexus approach supports greater policy coherence and alignment across sectors and scales. This approach is closely aligned with the objectives of several Sustainable Development Goals (SDGs), notably SDG 13 (Climate Action), SDG 6 (Clean Water and Sanitation), and SDG 15 (Life on Land), while also contributing indirectly to goals related to food security and poverty reduction (Smith *et al*., 2025). By encouraging cross-sectoral coordination and integrated planning, the nexus framework helps to identify pathways that maximize co-benefits and minimize trade-offs.

Table 1. Impacts of major climate mitigation strategies on carbon sequestration, water resources, and biodiversity.

Mitigation strategy	Carbon mitigation outcome	Water resource impacts	Biodiversity impacts	Key trade-offs / synergies	References
Afforestation / Reforestation	Increased biomass and soil carbon storage	Higher evapotranspiration; reduced streamflow in water-limited regions	Can enhance habitats if native species are used; risk of habitat degradation with monocultures	Synergies in degraded landscapes; trade-offs in arid regions	(Doelman *et al*., 2020; Cohen *et al*., 2021; Raymond *et al*., 2023; Yang *et al*., 2023)
BECCS	Potential net-negative emissions	High water demand for irrigation and processing; groundwater stress	Land conversion may threaten species-rich ecosystems	Carbon gains may offset by water scarcity and biodiversity loss	(Parkinson *et al*., 2019; Smith *et al*., 2022; Miralles-Wilhelm, 2023; de Silva *et al*., 2025)
Hydropower	Low-carbon electricity generation	Alters river flow regimes and sediment transport	Disrupts aquatic habitats and species migration	Trade-offs between energy security and ecosystem health	(Keith *et al*., 2021; Gérard *et al*., 2025)
Agrivoltaics	Carbon reduction via renewable energy	Reduced evaporation; improved water-use efficiency	Neutral to positive impacts if land use remains multifunctional	Strong nexus synergies when integrated	(Bussotti & Pollastrini, 2025)
Wetland restoration	Long-term carbon storage in soils	Improved water filtration and regulation	High biodiversity support	Triple-win nexus outcomes	(Wang *et al*., 2024)
Wastewater treatment optimization	Emission reductions via energy recovery	Water reuse and nutrient recycling	Indirect biodiversity benefits via reduced pollution	Synergies through circular resource use	(McDonald *et al*., 2024)

Operationalizing the nexus in policy and practice requires the application of analytical tools capable of capturing system-wide interactions. Methods such as life-cycle assessment, multi-criteria decision analysis, and scenario-based modeling are increasingly used to evaluate the environmental impacts of mitigation options across the carbon–water–biodiversity spectrum. These tools enable policymakers and practitioners to anticipate potential conflicts, assess long-term sustainability, and design adaptive strategies that balance competing objectives under changing climatic conditions (Ma *et al*., 2022). As such, the conceptual framework of the carbon–water–biodiversity nexus provides a critical foundation for advancing integrated and sustainable climate mitigation strategies (Carter & Miller, 2022; Johansson *et al*., 2022; Lee *et al*., 2022; Martyshuk *et al*., 2022; Fitero *et al*., 2023; Novak & Kralj, 2023).

Carbon mitigation strategies and their impacts on water resources

Climate mitigation strategies have traditionally emphasized carbon reduction and sequestration as primary objectives; however, these approaches can exert substantial pressures on water resources, resulting in complex trade-offs in both water availability and water quality. Land-based mitigation options are particularly influential, as they directly modify hydrological processes through changes in vegetation cover, land use, and management practices (Green *et al*., 2022; Skeie *et al*., 2022; Spirito *et al*., 2022; Karim & Rahman, 2023; Prada *et al*., 2024; Saif *et al*., 2024). Afforestation and reforestation, widely promoted as nature-based solutions (NBS), enhance carbon sequestration by increasing biomass and soil organic carbon stocks. At the same time, expanded forest cover typically leads to higher evapotranspiration rates, which can reduce surface runoff and groundwater recharge at the watershed scale (Raymond *et al*., 2023).

Empirical evidence indicates that the hydrological impacts of afforestation are highly context-dependent. In humid regions, increased evapotranspiration may have limited effects on water availability, whereas in arid and semi-arid environments, large-scale tree planting can significantly reduce streamflow and exacerbate water scarcity (Yang *et al*., 2023). Such reductions in water yield can affect downstream agricultural users, urban water supplies, and freshwater ecosystems, potentially undermining local climate adaptation and ecosystem resilience (Park & Petrenko, 2022; Ruiz *et al*., 2022; Sharma *et al*., 2022; Pérez *et al*., 2023; Alcoceba-Herrero *et al*., 2024; Cakmak *et al*., 2024; Liu *et al*., 2024). These findings highlight the importance of aligning carbon sequestration initiatives with regional hydrological constraints and water management objectives.

Bioenergy production represents another major mitigation pathway with pronounced water-related implications. Bioenergy crops, particularly those used in bioenergy with carbon capture and storage (BECCS), offer the potential for net-negative emissions by combining biomass energy generation with carbon sequestration. However, cultivating bioenergy feedstocks often requires substantial water inputs for irrigation, processing, and cooling, leading to increased competition with food production and heightened pressure on freshwater resources (Smith *et al*., 2022). In water-stressed regions, this competition may contribute to groundwater depletion and deteriorating water quality. Research from China demonstrates that land-use changes associated with bioenergy expansion have intensified interactions within the water–energy–food system, in some cases resulting in increased overall carbon emissions due to inefficiencies and resource trade-offs at the provincial level (Miralles-Wilhelm, 2023).

Low-carbon energy transitions further intersect with water systems through the deployment of renewable energy technologies. Hydropower remains a significant source of low-carbon electricity globally, yet its development often entails substantial alterations to river flow regimes, sediment transport, and seasonal hydrological patterns. These changes can compromise water security, disrupt aquatic ecosystems, and reduce the resilience of riverine biodiversity (Keith *et al*., 2021). In contrast, emerging integrated systems such as agrivoltaics demonstrate potential synergies across the nexus. By co-locating solar photovoltaic panels with agricultural production, agrivoltaic systems can reduce soil evaporation, moderate microclimates, and improve water-use efficiency while simultaneously generating renewable energy (Bussotti & Pollastrini, 2025).

Urban mitigation strategies also reflect carbon–water interactions, particularly within wastewater treatment systems. Wastewater treatment plants are energy-intensive infrastructures, yet they offer opportunities to optimize carbon reduction through energy recovery, water reuse, and nutrient recycling. Advanced treatment technologies can reduce greenhouse gas emissions while improving water quality and resource efficiency, thereby minimizing trade-offs between climate mitigation and urban water sustainability (McDonald *et al*., 2024). Collectively, these examples underscore the necessity of incorporating water-footprint assessments into climate mitigation planning to ensure that carbon reduction goals do not compromise hydrological sustainability.

Carbon mitigation and biodiversity conservation: synergies and trade-offs

The interface between carbon mitigation and biodiversity conservation presents significant opportunities for synergistic outcomes, while also posing risks of ecological trade-offs when mitigation strategies are narrowly designed. Nature-based solutions, including ecosystem restoration, protected area expansion, and sustainable land management, are increasingly recognized for their capacity to simultaneously sequester carbon and conserve biodiversity. Diverse ecosystems, such as forests, wetlands, and grasslands, generally store more carbon and provide greater ecosystem stability than simplified or monoculture systems (Doelman *et al*., 2022).

Mangrove restoration provides a prominent example of such synergy. Mangrove ecosystems function as highly efficient carbon sinks due to their high rates of biomass production and long-term carbon storage in sediments, while also supporting rich marine biodiversity and offering critical ecosystem services such as coastal protection and nursery habitats for fish species (Mariani *et al*., 2024). These multifunctional benefits position mangroves as a priority ecosystem within integrated mitigation and conservation strategies.

Nevertheless, trade-offs emerge when carbon sequestration objectives are prioritized without sufficient attention to ecological integrity. Afforestation initiatives that rely on fast-growing, non-native species may achieve rapid carbon accumulation but can degrade native habitats, alter soil properties, and reduce local species richness (Doelman *et al*., 2020). Similar challenges have been observed in REDD+ programs, where biodiversity outcomes depend heavily on governance structures and funding allocation mechanisms. In cases where financial incentives disproportionately favor carbon metrics, conservation efforts may overlook endemic or threatened species, thereby weakening biodiversity protection (Bonnet *et al*., 2024).

Bioenergy expansion poses additional risks to biodiversity, particularly when it drives land conversion in ecologically sensitive regions such as tropical forests and savannas (de Silva *et al*., 2025). Habitat loss and fragmentation associated with large-scale bioenergy plantations can reduce species populations and disrupt ecosystem processes. However, research suggests that sustainable intensification strategies, particularly within livestock and agricultural systems, can mitigate these trade-offs by increasing productivity on existing land and reducing pressure for further habitat conversion (Ellison *et al*., 2008).

Policy initiatives increasingly seek to address these complexities by integrating carbon and biodiversity objectives. Frameworks such as the European Union Green Deal emphasize ecosystem-based approaches and cross-sectoral coordination to maximize co-benefits across the nexus (Psomas *et al*., 2024). Complementary instruments, including ecological compensation schemes and biodiversity offset mechanisms, aim to counterbalance unavoidable impacts by restoring or enhancing equivalent habitats elsewhere (Kim *et al*., 2022). While such mechanisms remain subject to debate, they represent an evolving effort to reconcile carbon mitigation with biodiversity conservation within policy and planning processes.

Water management in the context of climate mitigation and biodiversity

Water management occupies a central position within the carbon–water–biodiversity nexus, mediating interactions between climate mitigation efforts and ecosystem health. Integrated water resource management (IWRM) frameworks offer a pathway to align water allocation, land use, and energy production with carbon mitigation objectives. By improving water-use efficiency in carbon-intensive sectors such as agriculture, IWRM can reduce emissions associated with irrigation, fertilizer use, and land degradation, while simultaneously supporting the conservation of aquatic and terrestrial ecosystems (Sonter *et al*., 2020).

At broader spatial scales, the concept of virtual water trade highlights the transboundary nature of nexus interactions. In regions such as the Greater Horn of Africa, exports of water-intensive agricultural products effectively transfer water resources embedded in commodities, influencing local water availability, biodiversity, and climate resilience (Heinonen *et al*., 2021). These dynamics illustrate how water management decisions made within global supply chains can have far-reaching environmental consequences at local and regional levels.

Trade-offs become particularly evident in the context of hydropower development, where water diversions and flow regulation can disrupt riverine biodiversity. Altered flow regimes may impede fish migration, modify sediment transport, and degrade riparian habitats, leading to long-term ecological impacts (Gérard *et al*., 2025). Conversely, synergies are apparent in wetland restoration initiatives, which enhance carbon sequestration through organic matter accumulation, improve water quality through filtration and nutrient retention, and provide critical habitats for diverse species (Wang *et al*., 2024).

Case studies from Nepal further demonstrate how food system analyses grounded in water–energy–biodiversity perspectives can identify pathways to reduce trade-offs and enhance resilience. Sustainable agricultural practices, combined with efficient water use and ecosystem conservation, contribute to improved food security while supporting climate mitigation goals (Fajardy & Mac Dowell, 2018). In urban contexts, green infrastructure solutions—such as green roofs, constructed wetlands, and permeable surfaces—integrate nexus elements by reducing stormwater runoff, lowering urban heat, sequestering carbon, and enhancing urban biodiversity (Heck *et al*., 2016).

Together, these examples emphasize that effective water management is indispensable for achieving integrated climate mitigation outcomes that safeguard both biodiversity and ecosystem services.

Integrated nexus approaches in global land use optimization

Integrated land-use optimization represents one of the most tangible applications of the carbon–water–biodiversity nexus, as land systems simultaneously support food production, water regulation, energy generation, and carbon sequestration. Global-scale modeling studies increasingly demonstrate that land-use strategies designed around single objectives often intensify trade-offs, whereas balanced, multi-objective allocation can substantially improve overall sustainability outcomes. Recent global assessments indicate that optimizing land use across food, water, energy, and carbon priorities can minimize systemic trade-offs while delivering biodiversity gains, particularly through the strategic expansion and effective management of protected areas (Donnison & McCulloch, 2020). These findings suggest that conservation-oriented land zoning, when combined with sustainable intensification elsewhere, can reconcile competing demands without compromising ecosystem integrity.

Quantitative analyses further reveal that synergies within the water–land–food–climate nexus are achievable when land-use changes are explicitly aligned with climate mitigation goals. Studies examining alternative land-use scenarios show that practices such as agroforestry, diversified cropping systems, and ecosystem restoration can enhance water-use efficiency, stabilize carbon stocks, and support biodiversity conservation, provided that trade-offs are proactively identified and managed (Muratori *et al*., 2021). These results underscore the importance of spatial planning tools and integrated models that capture cross-sectoral interactions, enabling policymakers to anticipate outcomes across multiple environmental dimensions rather than optimizing in isolation.

In regional contexts, particularly in Europe, biodiversity has been increasingly recognized as a functional component of the nexus rather than a passive beneficiary. Biodiversity-rich green infrastructure contributes to carbon sequestration, urban cooling, flood mitigation, and water regulation, while simultaneously supporting transport efficiency and public health outcomes through improved air quality and recreational spaces (Baldwin-Cantello *et al*., 2023). Such multifunctional landscapes exemplify how ecosystem-based planning can generate co-benefits across traditionally disconnected policy domains.

Table 2. Regional applications of the carbon–water–biodiversity nexus in climate mitigation.

Region / country	Nexus focus	Key findings	Policy relevance	References
China	Land-use change; water–energy–food–carbon	Urban expansion increases trade-offs; ecological restoration creates synergies	Importance of spatial planning and restoration policies	(Miralles-Wilhelm, 2023)
Greater Horn of Africa	Virtual water trade; food–biodiversity–health	Imports reduce local water stress and biodiversity pressure	Regional cooperation and equitable trade strategies	(Heinonen *et al*., 2021)
Tanzania	Livestock intensification	Reduced land expansion; improved carbon storage and biodiversity	Sector-specific nexus interventions	(Ellison *et al*., 2008)
Nepal	Agroforestry; food systems	Improved water retention, carbon sequestration, and biodiversity	Climate-resilient rural development	(Fajardy & Mac Dowell, 2018)
Global (REDD+)	Equity in fund distribution	Equitable allocation enhances carbon and biodiversity outcomes	Governance and finance design	(Eisenhauer *et al*., 2024)
Europe	Green infrastructure	Carbon sinks, water regulation, health co-benefits	Urban and regional planning integration	(Baldwin-Cantello *et al*., 2023)

Circular economy principles further reinforce nexus integration, especially within food systems. Food waste reduction and resource recovery strategies reduce upstream land and water demands, lower greenhouse gas emissions, and alleviate pressure on ecosystems. By closing material loops through composting, anaerobic digestion, and nutrient recycling, circular food systems directly connect carbon mitigation with water conservation and biodiversity protection (Yirdaw *et al*., 2023). These approaches demonstrate how demand-side interventions can complement land-use optimization strategies, reducing the need for additional resource extraction and land conversion.

Case studies: regional applications of the nexus

Empirical case studies provide critical insights into how nexus dynamics unfold across different socio-ecological contexts, highlighting the importance of place-based governance and adaptive management. In China, land-use change has been shown to exert heterogeneous effects on water–energy–food–carbon interactions. Rapid urban expansion has intensified trade-offs by increasing resource demand and emissions, whereas ecological restoration and land rehabilitation programs have generated synergies by enhancing carbon sequestration, improving water regulation, and stabilizing ecosystems (Miralles-Wilhelm, 2023). These contrasting outcomes illustrate how policy direction and land-use planning determine whether nexus interactions become reinforcing or conflicting.

In Africa's Greater Horn region, nexus pressures are amplified by climate variability, population growth, and limited infrastructure. Studies emphasize that virtual water trade—through the import of water-intensive food commodities—can alleviate local water stress while supporting food security and reducing biodiversity loss. When strategically managed, such approaches can also deliver health co-benefits by improving nutrition and resilience to climate shocks (Heinonen *et al*., 2021). However, their success depends on governance capacity and equitable access to resources, reinforcing the need for integrated regional strategies.

At smaller spatial scales, evidence from Tanzania demonstrates that sustainable livestock intensification can significantly reduce agro-environmental trade-offs. By improving feed efficiency, grazing management, and animal health, these systems enhance productivity without expanding land use, thereby conserving water resources, increasing soil carbon storage, and protecting surrounding biodiversity (Ellison *et al*., 2008). This case highlights how sector-specific interventions, when aligned with nexus principles, can deliver multi-dimensional benefits.

Similarly, Nepal's food system analysis underscores the value of integrating water, energy, and biodiversity considerations into climate mitigation planning. Agroforestry systems emerge as particularly effective, buffering climate impacts by improving water retention, stabilizing slopes, enhancing carbon sequestration, and supporting diverse species assemblages (Fajardy & Mac Dowell, 2018). These systems also contribute to rural livelihoods, demonstrating the social benefits of nexus-informed approaches.

At the global scale, analyses of REDD+ fund distribution reveal that equity-oriented allocation mechanisms improve both biodiversity conservation and carbon mitigation outcomes. Models indicate that when financial resources are directed toward regions with high biodiversity value and strong governance frameworks, trade-offs are minimized and long-term sustainability is enhanced (Eisenhauer *et al*., 2024). Collectively, these case studies reinforce that nexus management is inherently context-specific and that successful outcomes depend on integrating ecological, social, and economic dimensions within land-use decision-making frameworks.

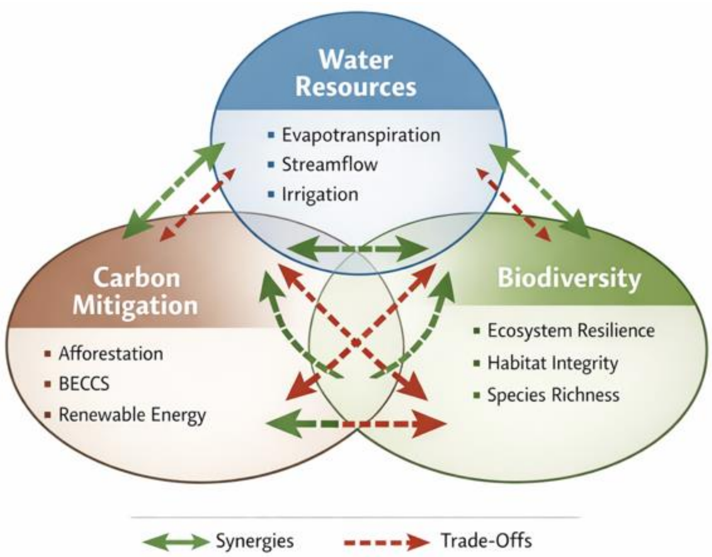

Figure 1. Conceptual framework of the carbon–water–biodiversity nexus in climate mitigation policies. The figure illustrates bidirectional interactions and feedbacks among carbon mitigation strategies, water resources, and biodiversity. Carbon-focused interventions (e.g., afforestation, BECCS, renewable energy) influence hydrological processes through changes in evapotranspiration, water demand, and flow regulation, while simultaneously affecting biodiversity via habitat modification and ecosystem restoration. Biodiversity enhances carbon sequestration and water regulation through ecosystem resilience and service provision. Water availability mediates both carbon uptake and biodiversity outcomes. Synergies and trade-offs are shown as reinforcing or conflicting pathways, highlighting the need for integrated, nexus-based policy design.

RESULTS AND DISCUSSION

The carbon–water–biodiversity nexus provides a critical analytical lens for evaluating the effectiveness and long-term sustainability of climate mitigation policies, revealing a complex landscape of interactions that extend well beyond carbon-centric outcomes. As synthesized in this review, mitigation strategies frequently generate outcomes that are simultaneously beneficial and detrimental across different environmental dimensions. Pairwise interactions—most notably carbon–water and carbon–biodiversity linkages—are evident in widely promoted mitigation approaches such as afforestation and bioenergy with carbon capture and storage (BECCS). While these strategies can deliver substantial carbon sequestration benefits, they may also induce water depletion, alter hydrological regimes, or reduce biodiversity when implemented without integrated planning (Baldwin-Cantello *et al*., 2023; Bayer *et al*., 2023). Incorporating biodiversity as a third and foundational dimension amplifies these dynamics, as diverse ecosystems not only enhance carbon storage through greater resilience and functional redundancy but also regulate water cycles through improved infiltration, evapotranspiration balance, and water purification processes (Cohen *et al*., 2021).

The findings demonstrate that nexus-informed strategies can enable so-called triple-win outcomes, where carbon mitigation, water security, and biodiversity conservation reinforce one another. However, the review also highlights that poorly integrated or narrowly targeted policies risk intensifying trade-offs, particularly in regions characterized by water scarcity, ecological sensitivity, or limited governance capacity. These results reinforce the central argument that climate mitigation policies designed in isolation are insufficient and, in some cases, counterproductive, underscoring the necessity of adopting nexus-based frameworks in policy formulation and implementation.

A key insight emerging from the thematic analysis is the pivotal role of nature-based solutions (NBS) in navigating nexus interactions. NBS, including wetland restoration, agroforestry, and ecosystem rehabilitation, consistently demonstrate the potential to deliver multiple co-benefits by simultaneously addressing carbon mitigation, water regulation, and biodiversity conservation (Parkinson *et al*., 2019; Hirwa *et al*., 2021). For example, mangrove restoration projects represent a particularly robust nexus intervention, offering long-term carbon sequestration while enhancing water quality, stabilizing coastlines, and supporting diverse marine and terrestrial species. Nevertheless, the effectiveness of such interventions is highly contingent on local hydrological conditions, governance structures, and community participation. Inadequate consideration of these contextual factors can lead to unintended outcomes, such as altered species composition or displacement of local biodiversity, thereby undermining the intended benefits (Yirdaw *et al*., 2023).

Scale emerges as a critical determinant of nexus outcomes. While localized or landscape-scale NBS often yield positive synergies, large-scale implementation—such as global afforestation initiatives—can generate adverse effects, particularly in arid and semi-arid regions. In such contexts, increased vegetation water demand may reduce streamflow and groundwater availability, placing additional stress on water-dependent ecosystems and species (Samberger, 2022). This spatial heterogeneity highlights a central challenge in nexus governance: benefits realized at one scale or in one region may translate into costs elsewhere. Consequently, mitigation planning must be grounded in place-based assessments that account for regional ecological thresholds, hydrological constraints, and biodiversity values rather than relying on uniform global solutions.

The discussion further underscores the importance of social and equity dimensions embedded within the carbon–water–biodiversity nexus. Climate mitigation strategies that overlook social contexts risk exacerbating existing inequalities, particularly in developing regions where biodiversity hotspots frequently overlap with water-stressed landscapes and vulnerable populations (Jamion *et al*., 2023). Bioenergy expansion provides a salient example, as land and water competition associated with bioenergy crop cultivation can reduce access to food, water, and livelihoods for local communities, thereby undermining social acceptance and the durability of mitigation outcomes (Eisenhauer *et al*., 2024). The case studies reviewed, particularly those from China and Africa, demonstrate that integrated nexus approaches incorporating stakeholder engagement, participatory governance, and equitable resource allocation can mitigate such risks and improve both environmental and social outcomes (Paleari, 2024).

The nexus perspective also strengthens alignment between climate mitigation and the Sustainable Development Goals (SDGs). By explicitly addressing interactions among carbon management, water security, and biodiversity protection, nexus-based policies can advance SDG 13 (Climate Action), SDG 6 (Clean Water and Sanitation), and SDG 15 (Life on Land) simultaneously. However, achieving such alignment requires robust governance frameworks capable of managing trade-offs across sectors and scales, as well as institutional coordination that transcends traditional administrative boundaries (Vargas *et al*., 2023). Without these enabling conditions, the potential of nexus approaches to support sustainable development remains constrained.

Despite growing recognition of the nexus concept, significant knowledge (Saeed, 2022; Khalil, 2023; Saeed *et al*., 2023; Ghati *et al*., 2024) gaps persist, particularly in the quantitative assessment of tri-dimensional interactions under future climate scenarios. While modeling tools have advanced in capturing pairwise trade-offs, integrated simulations that simultaneously represent carbon, water, and biodiversity dynamics remain limited. Many existing models inadequately represent feedback mechanisms, such as the role of biodiversity in enhancing ecosystem resilience to water stress and stabilizing carbon stocks under climatic extremes (Smith *et al*., 2025). Addressing these gaps will require improved data integration across disciplines, leveraging advances in remote sensing, long-term ecological monitoring, and participatory data collection, including citizen science initiatives (Ma *et al*., 2022).

Emerging technologies also warrant closer examination within the nexus framework. Innovations such as precision agriculture, digital water management systems, and advanced carbon capture technologies have the potential to reduce resource inefficiencies and mitigate trade-offs. However, their broader implications for biodiversity and water systems remain underexplored, particularly at large scales and in low-income contexts (Raymond *et al*., 2023). Future research should therefore prioritize holistic assessments of technological solutions to ensure that efficiency gains in one domain do not generate hidden costs in others.

Overall, the carbon–water–biodiversity nexus challenges traditional siloed approaches to climate policy and resource management, advocating instead for cross-sectoral collaboration and systems-based decision-making. By prioritizing synergies and explicitly addressing trade-offs, nexus-informed policies can enhance ecological and social resilience in the face of climate change. Realizing this potential, however, will require overcoming institutional fragmentation, investing in integrated monitoring and evaluation systems, and fostering adaptive governance capable of responding to dynamic environmental and socio-economic conditions (Yang *et al*., 2023).

CONCLUSION

In conclusion, this review underscores the imperative of adopting a carbon–water–biodiversity nexus perspective in climate mitigation policies to balance trade-offs and harness synergies for sustainable outcomes. The synthesis reveals that while mitigation strategies hold promise for multi-dimensional benefits, their success hinges on holistic planning that accounts for interconnected environmental systems (Smith *et al*., 2022; Miralles-Wilhelm, 2023). Key takeaways include the potential of NBS to deliver co-benefits, the risks of trade-offs in resource-constrained regions, and the need for equitable policy frameworks to ensure inclusive climate action (Keith *et al*., 2021).

Future research should focus on developing advanced integrated models that incorporate dynamic feedback loops and scenario analyses under various climate projections (Bussotti & Pollastrini, 2025). Additionally, empirical studies in under-represented regions, such as Southeast Asia and Latin America, are essential to capture diverse nexus dynamics (McDonald *et al*., 2024). Policy recommendations include mainstreaming nexus thinking in international agreements, like the Paris Agreement and Convention on Biological Diversity, through indicators that track tri-dimensional impacts (Doelman *et al*., 2022). Ultimately, fostering interdisciplinary collaboration and innovative financing mechanisms will be crucial to translate nexus insights into actionable strategies for a resilient future (Mariani *et al*., 2024).

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