TECHNICAL REPORT

THE NATURE-CLIMATE-FOOD NEXUS

Exploring the Interconnections and Synergies Across Rice Ecosystems, Forests, Wetlands, and Climate Pathways

November 2025

Imprint

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Front Page: International Rice Research Institute

Suggested Citation

Kemp, B., Urfels, A., Mirzabaev, A. (2025) *The Nature-Climate-Food Nexus: Exploring the Interconnections and Synergies Across Rice Ecosystems, Forests, Wetlands, and Climate Pathways*. Los Baños, Philippines: International Rice Research Institute, 37 pages

Acknowledgements

This work originated from an idea proposed by Dr. Yvonne Pinto, whose vision and encouragement shaped the early direction of the paper. We are grateful to Dr. Jon Hellin for his valuable comments and constructive feedback on earlier versions of the paper. We would also like to thank the participants of the SIRS-IRRI research seminar for their insightful feedback and suggestions, which helped to strengthen and refine the final version of this report.

International Rice Research Institute

The International Rice Research Institute (IRRI) is a non-profit scientific research organization and a member of the CGIAR, dedicated to reducing poverty and hunger, improving the health and welfare of rice farmers and consumers, and ensuring the environmental sustainability of rice production systems.

Executive Summary

Rice-based agri-food systems are an integral element of the nature–climate–food nexus: rice is an important staple for over half the global population, anchors global food security, and shapes ecosystems that regulate climate and water. Being sustained by and driving ecological processes, rice cultivation, on one hand, depends on forests that generate rainfall, wetlands that buffer floods and recycle nutrients, and biodiversity that stabilizes yields under stress, while in turn contributing to water storage and regulation, biodiversity habitat provision, and nutrient cycling within these landscapes. Yet these very ecosystems are under mounting pressure from deforestation, wetland loss, and input-intensive farming. Such disruptions weaken hydrological regulation, carbon storage, nutrient cycling, and yield stability that threaten to erode the resilience of rice landscapes. Protecting ecological foundations is therefore essential for safeguarding rice production and nature to meet global goals on food security, climate resilience, and sustainable development. At the same time, rice systems will also need to adjust and align with shifting water and climate conditions to remain resilient.

What does this mean for rice sector policies?

- **Knowledge & extension**: there is an urgent need to strengthen and scale up environmentally-friendly practices (e.g., rice–fish, flood-based farming) through extension, digital tools, and participatory monitoring; use analytical tools to show associated trade-offs and co-benefits.
- **Integrated governance and planning**: countries will benefit from using integrated regional landscape and spatial planning to align rice cultivation with forest, wetland, and watershed management; and foster cross-agency coordination.
- **Finance & incentives**: Scaling environmentally friendly rice cultivation requires expanding payments for ecosystem services (PES), green bonds, carbon and blue carbon markets to reward conservation; ensure revenues flow to communities as livelihood benefits.
- **Certification**: Promote the use of rice certification labels reward sustainable water use, low emissions, and biodiversity; link to procurement and carbon markets.
- **Sustainable consumption**: Green public procurement and repurposing subsidy systems for environmental purposes; strengthening export and domestic markets for traceable, eco-friendly rice.

In this paper, drawing from emerging research, we seek to reframe rice agriculture within a broader ecological landscape, spotlighting critical ecosystem-driven processes that conventional approaches typically neglect. By bridging scientific insights with practical strategies, we aim to catalyze transformative, cross-sectoral actions that simultaneously safeguard rice yields and protect ecosystem health.

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Abbreviations

AMD	Asian Mega-Deltas (CGIAR Initiative on Asian Mega-Deltas)
AR	Atmospheric River
AWD	Alternate wetting and drying
BOD	Biological Oxygen Demand
CGIAR	Consultative Group on International Agricultural Research
ECRL	Ecological Conservation Redline (China's land-use policy)
FAO	Food and Agriculture Organization of the United Nations
GCM's	Global Climate Models
GHG	Greenhouse Gas
HKH	Hindu Kush Himalaya
IGP	Indo-Gangetic Plain
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Intertropical Convergence Zone
IVT	Integrated Vapor Transport
LULCC	Land Use Land Cover Change
MAR	Managed aquifer recharge
MEA	Millenium Ecosystem Assessment
$Mg\ C\ ha^{-1}$	Mega grams of Carbon per Hectare
NbS	Nature-based solutions
PES	Payments for ecosystem services
Pg C	Peta grams of Carbon
RASp	Rice–Aquatic Species Integration Systems
SDG	Sustainable Development Goal
SEA	Southeast Asia
SOC	Soil Organic Carbon
SRP	Sustainable Rice Platform
UNEP	United Nations Environment Program
WMO	World Meteorological Organization
$\mu g\ C\ g^{-1}$	Micrograms of carbon per gram of soil
$Tg\ C\ yr^{-1}$	Tera grams of Carbon per year

1. Introduction

The nature–climate–food nexus constitutes a deeply interconnected system, reflecting the close interdependence between ecosystems, climate processes, and food production. Rice is at the heart of this nexus. As the staple food for more than half of the world's population, rice provides over 21% of global dietary energy and up to 76% of calories consumed in Southeast Asia (Zhao *et al.*, 2020). More than 90% of global rice is produced in Asia, underscoring its central role in both regional and global food security (Mohidem *et al.*, 2022). However, rice cultivation does not occur in isolation: it both depends upon, and reshapes surrounding ecosystems. For example, agricultural expansion remains a primary driver of ecological change, responsible for nearly 90% of global deforestation, as forests are permanently converted to cropland and pasture (FAO, 2021).

In tropical deltas and uplands, rice fields are embedded within forests, wetlands, and riparian corridors that regulate water flows, sequester carbon, and sustain biodiversity. These coupled landscapes not only buffer floods and recharge aquifers but also intersect with atmospheric rivers (narrow, moisture-laden air currents) that transport water vapor across continents and deliver much of the monsoonal rainfall essential for rice basins, particularly in the Mekong and Ganges deltas. In this way, rice systems rely on complex ecological feedback that extend far beyond field boundaries.

At the same time, the expansion and intensification of rice agriculture can undermine these ecological foundations. Deforestation, wetland drainage, and biodiversity loss weaken hydrological regulation, while input-intensive practices contribute to greenhouse gas emissions, nutrient runoff, and habitat fragmentation. These processes generate environmental disservices that threaten the resilience of rice cultivation itself. The trade-off is increasingly clear: short-term yield gains achieved through ecological simplification can erode the long-term stability of food systems.

This review situates rice production within the broader nature–climate–food nexus, recentering nature as active infrastructure that rice systems are part of rather than a passive backdrop. The review begins with forests and Atmospheric Rivers (ARs), exploring their role in recycling and transporting green water to sustain monsoonal rainfall. It then turns to agroforestry and local water dynamics, before examining biodiversity, agrobiodiversity, and microbiomes as drivers of resilience. Building on this, the analysis considers ecosystem services and disservices of rice landscapes, with examples of wetlands and mangroves, before concluding with policy pathways for adaptation and ecological stewardship.

1.1 Exceeding Planetary Boundaries

Rising food demand and mounting climate pressures have increased the urgency of transitioning to environmentally sustainable and highly productive agricultural practices. Figure 1 shows the planetary boundaries framework, developed by the Stockholm Resilience Centre. It identifies nine critical Earth system processes that regulate the planet's stability and resilience – including climate, biodiversity, land use, and nutrient cycles. Crucially, it shows that six of the nine planetary boundaries have been crossed. An alarming development from previous frameworks in 2009 and 2015, which showed three and four boundaries crossed from an identified seven at the time. Crossing these boundaries raises the risk of triggering large-scale abrupt, or irreversible environmental changes. Whilst these consequences may not be immediate, the boundaries represent a safe operating space, in which crossing will bring risks to societies and the biosphere we depend on (Richardson *et al.*, 2023). In this context, the nature–climate–food nexus provides a framework for understanding these interconnected pressures.

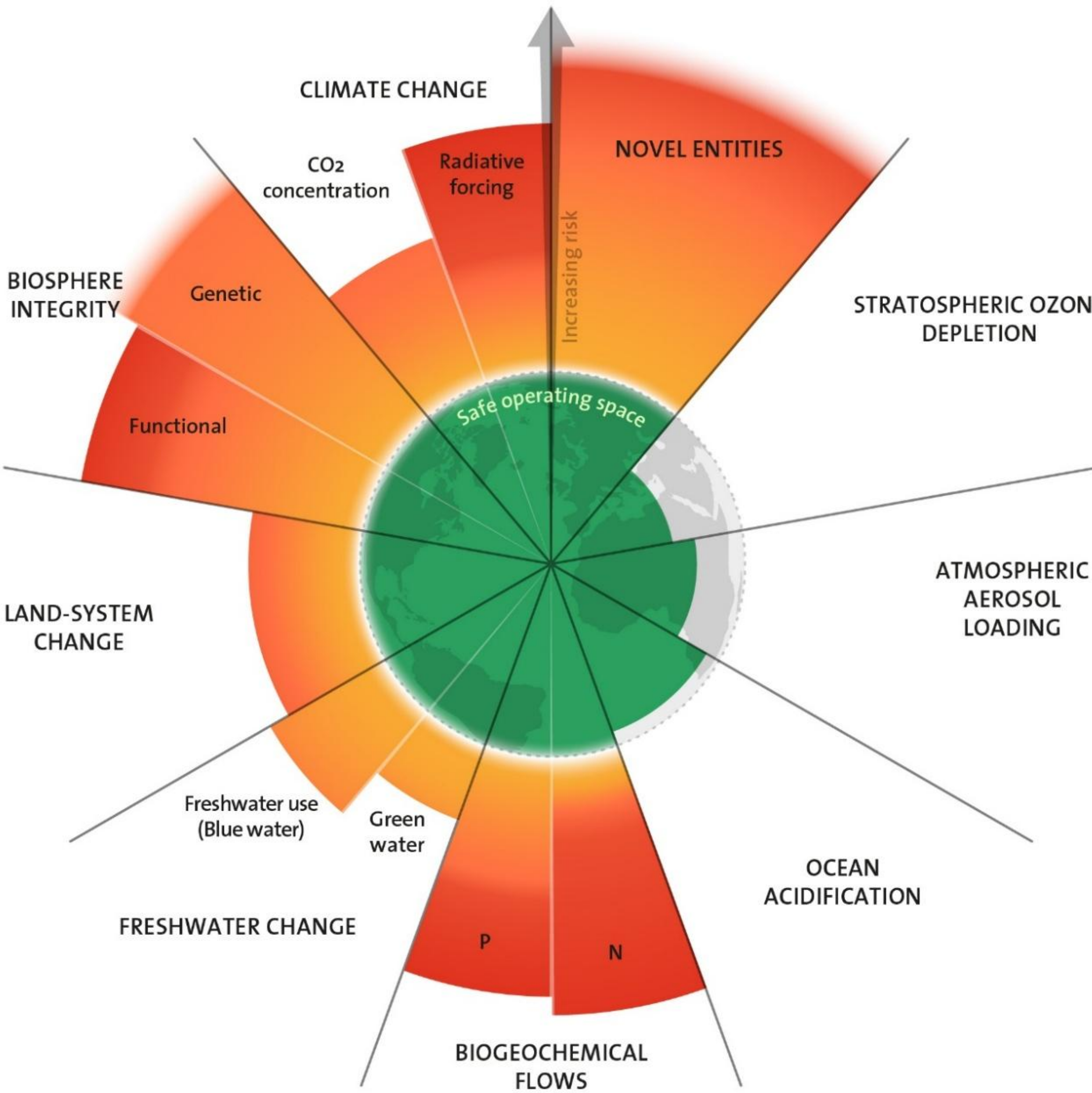

Figure 1: The 2023 Planetary Boundaries framework. Licensed under CC BY-NC-ND 3.0. Credit: Azote for Stockholm Resilience Centre, based on Richardson et al. (2023)

1.2 Sustainable Development Goals (SDGs)

Utilizing the synergies and addressing the tradeoffs of the nature-climate-food nexus is important for achieving SDGs 2 (Zero Hunger), 12 (Responsible Consumption and Production), 13 (Climate Action) and 15 (Life on Land) for both productive and sustainable agriculture. Between 2010 and 2050, global food consumption is expected to grow by 35–56 percent because of population growth, rising incomes and dietary shifts (van Dijk *et al*. 2021). At the same time, 2024 marked the warmest year on record, global temperatures averaged 1.55 °C above the 1850–1900 pre-industrial baseline, surpassing the 1.5 °C threshold for the first time (WMO 2025). Understanding this nexus is essential not only for achieving SDGs 2, 12, 13 and 15 but also for navigating the synergies and trade-offs that connect all seventeen SDGs.

1.3 The Role of Rice Varietal Development within the Nexus

While ecological processes form the foundation of rice production, rice breeding remains critical for shaping how rice systems interact with their environments. At IRRI and across CGIAR, breeding has traditionally targeted yield potential, pest resistance, and tolerance to abiotic stress. Increasingly, however, these priorities intersect directly with the nature–climate–food nexus. Stress-tolerant rice varieties for drought, submergence, or salinity, reduce vulnerability to climate extremes and lessen dependence on costly or ecologically damaging interventions. Breeding lines with improved root architecture or nitrogen-use efficiency can reduce fertilizer demand and nutrient runoff, while low-methane-emitting varieties contribute to climate mitigation goals.

By aligning breeding strategies with ecosystem stewardship, IRRI's programs are positioned to deliver varieties that not only sustain productivity under intensifying climate stress but also reinforce ecological resilience. In this sense, rice breeding can operate as a bridge between natural infrastructure and agricultural outcomes, providing an avenue to synergize food security, climate adaptation, and environmental sustainability within rice-based systems.

1.4 Objectives of this Report

This technical report aims to re-center nature as a foundational component of the nexus, rather than a backdrop to climate and food policies. Beyond exploring how climate change and food systems interact, we will ask: What critical functions do forests, wetlands, soils and rice systems perform in stabilizing carbon and water cycles, supporting biodiversity and regulating greenhouse gases? And what cascading impacts arise when those functions erode? By deepening the ecological lens, often overlooked in rice research, we aim to illuminate both the hidden value of nature's infrastructure and the massive costs of its degradation.

2. Atmospheric Rivers (ARs) and Forest–Climate Linkages

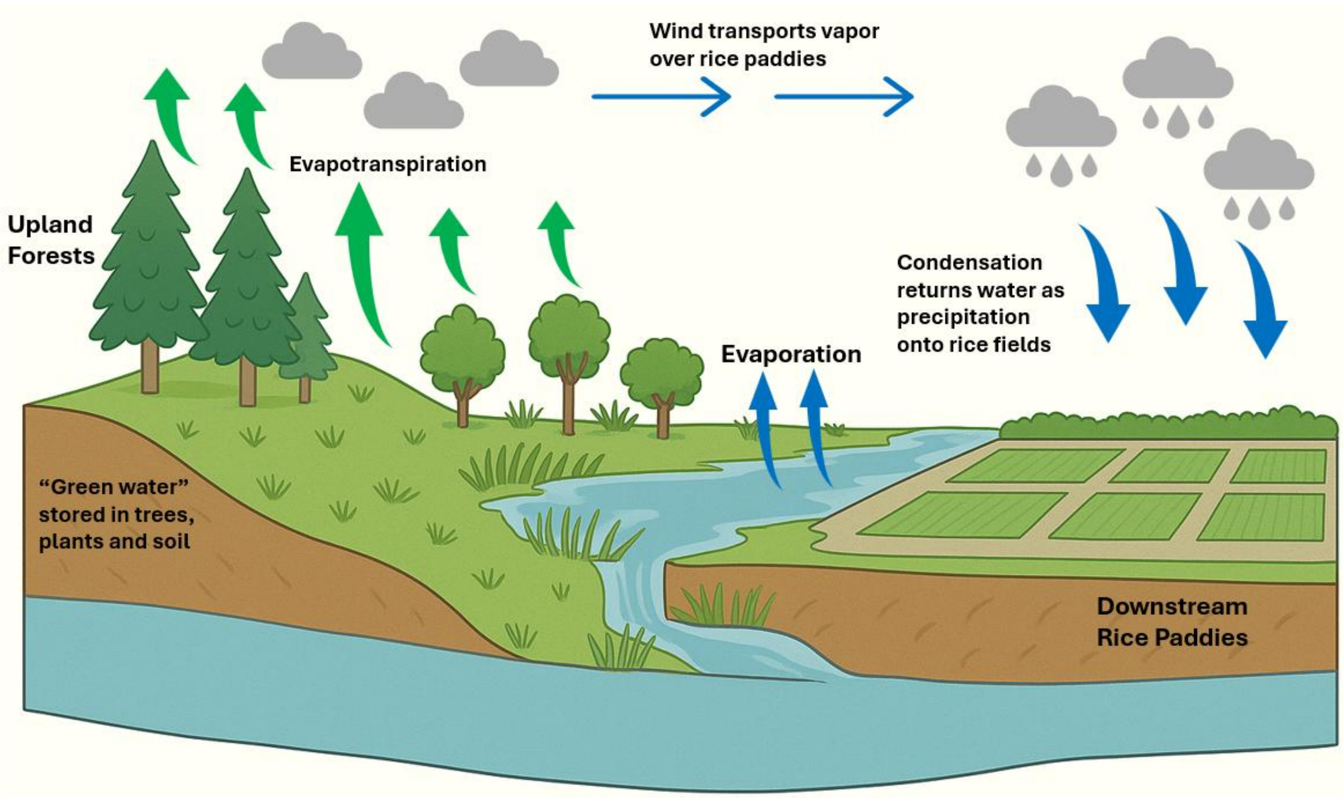

Figure 2: The Green Water Cycle

2.1 Forests as moisture engines

Forests play a pivotal role in the water cycle, regulating both local and regional climates through evapotranspiration. Between 2001 and 2019, they sequestered twice as much CO_2 as they emitted, acting as a net carbon sink of 7.6 Gt CO_2 yr^{-1} – one and a half times greater than annual US emissions (Harris & Gibbs, 2021). In tropical regions, forests "recycle" soil moisture (green water) back to the atmosphere, enhancing local and downwind rainfall (FAO, 2019).

A discovery made by Brazilian scientist Eneas Salati illustrates this process. Using the fact that not all water is the same - hydrogen and oxygen can vary in atomic mass, forming different isotopes. In 1979 by tracking isotopes as they moved through the water system from the Atlantic to the Peruvian border, he discovered that nearly half of the rain falling over the Amazon was not from the ocean, but from the forest itself. He found that around 75% of rainfall is recycled through evaporation and transpiration, with the same water vapor reused 5–6 times (Salati, 1979). This recycled moisture feeds into large-scale atmospheric circulation systems, including atmospheric rivers (ARs).

Building on Salati's work, Makarieva and Gorshkov proposed the "biotic pump" theory, which frames forests as active drivers of atmospheric circulation. They argued that intense evapotranspiration and condensation over forests lowers air pressure above the canopy, creating horizontal pressure gradients that draw moist air inland from the ocean

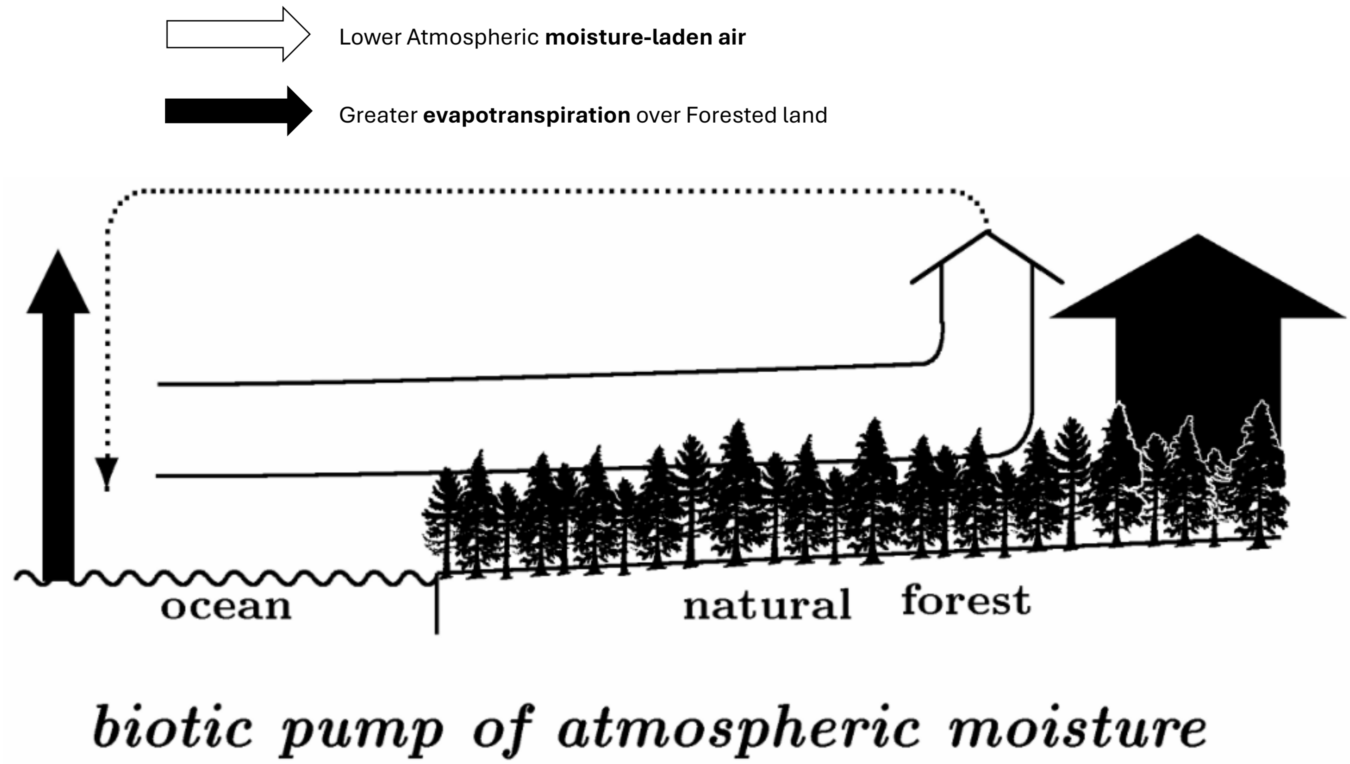

Figure 3: Forests as "biotic pumps," recycling moisture to fuel atmospheric rivers and sustain downwind rainfall. Adapted from Makarieva & Gorshkov, 2007). Licensed under a Creative Commons Attribution License.

(Makarieva & Gorshkov, 2010). When forest cover is continuous, this biotic pump enables long-distance transport of atmospheric moisture, supporting rainfall far beyond the forest edge. However, when forests are cleared or fragmented, that moisture transport breaks down. Downwind areas, like rice farms, get less rain, especially during critical growing seasons. This process underpins what Stark *et al*. (2016) describe as "ecoclimate teleconnections"- vegetation change in one region altering climate and vegetation in others. Upland forests act as "moisture engines," their high evapotranspiration seeding atmospheric rivers that deliver wet-season rains to rice basins such as the Mekong and Ganges. Van Noordwijk *et al*. (2014) frame this as "rainbow water" - atmospheric moisture generated by vegetation. Fast-growing trees can return 200–300 mm yr^{-1} of green water to the atmosphere, but clearing them, while temporarily boosting blue-water runoff (~3,000 km^3 yr^{-1}), sacrifices this recycling and weakens downwind rainfall regimes. Protecting upland tree cover is therefore critical for maintaining reliable AR and monsoon rainfall that rice systems depend upon.

2.2 Importance of Atmospheric Rivers

Atmospheric rivers (ARs) are long, narrow corridors of enhanced water-vapor transport. They are typically identified when integrated vapor transport (IVT) exceeds 250 kg m^{-1} s^{-1} across contiguous grid cells, forming narrow plumes that can extend thousands of kilometers (Reid *et al.*, 2020). For rice landscapes, ARs are not an abstract concept but a key delivery mechanism of wet-season rainfall into monsoon basins. Most of this moisture originates over the tropical oceans, while land-based evapotranspiration from the Ganges Basin and other uplands provides a crucial supplementary source that sustains rainfall as the season progresses. Studies show that terrestrial recycling contributes up to 20–25 % of late-season rainfall in parts of India, helping to extend monsoon duration and maintain soil moisture during critical cropping periods (Pathak et al., 2014; 2017). When forests remain intact, ARs deliver reliable, high-volume rainfall during critical sowing and growing periods. When forest cover is degraded however, the intensity and routing of ARs weaken or shift, leaving rice systems vulnerable to delayed monsoons, shorter wet seasons, and more erratic precipitation.

2.3 Croplands as Evapotranspiration Supplier

In some major rice-growing regions, croplands themselves are significant sources of evapotranspiration (ET), particularly where irrigation sustains water availability through the dry season. In the Indo-Gangetic Plain (IGP), the largest alluvial plain in the world, cropland covers over 72% of the basin (World Bank, 2010; after Humphreys et al., 2008), while forests occupy only a small residual fraction of 3–8% across core plains states such as Punjab, Haryana, Uttar Pradesh and Bihar (FSI, 2023, Ch. 2). Consequently, cropland ET is a major component of land–atmosphere coupling. Lagrangian moisture-tracking identifies the Ganges basin as the dominant terrestrial source of Indian Summer Monsoon Rainfall (ISMR), supplying ~15% of monsoon precipitation to northern and central India (Pathak et al., 2016). At the subcontinental scale, the continental moisture recycling ratio peaks at ~20–40% in July, underscoring the substantial role of land-surface ET during the mid-monsoon. This recycled contribution strengthens as the season progresses, when soil moisture recharge activates cropland ET (Pathak et al,. 2014).

Shallow groundwater is particularly important later in the season: as soils and near-surface aquifers store and release water, land-surface ET can continue to contribute to rainfall even as the proportional influence of oceanic sources declines. Because groundwater responds more slowly to meteorological drought than rivers and reservoirs, it provides a lagged buffer, helping maintain ET and crop water supply during drier years. Ongoing groundwater depletion in parts of the IGP risks eroding this buffering function, weakening late-season ET.

Human water management further alters the surface energy and moisture budgets, with climate scale effects. Multi model IRRMIP experiments show that irrigation expansion increases latent heat flux and reduces sensible heat and upwelling longwave, making 2-m hot-temperature extremes 4 times less likely over heavily irrigated belts (Yao et el., 2025). In the IGP, regional modelling and satellite-constrained studies report about 2 °C pre-monsoon cooling attributable to irrigation, consistent with broader evidence that irrigation suppresses hot-day extremes across South Asia; however, using observed seasonal irrigation, Jha et al. (2022) show that pre-monsoon cooling is much smaller (earlier studies overestimated it by about 4.9×), and a 2.5% rise in humidity can erode the apparent relief in moist-heat metrics.

Overall, irrigation is a significant modifier of the near-surface energy and moisture budgets: it shifts energy toward latent heat, cools the boundary layer, and reduces the frequency of hot extremes. Yet the net heat-stress benefit can be limited by higher humidity and remains contingent on water availability—particularly where groundwater pumping draws down shallow aquifers. In practical terms, intensified cropland ET shapes the local temperature–humidity background that influences how monsoon rainfall develops and persists later in the season. The durability of these feedbacks depends on sustainable groundwater and irrigation management.

2.4 Deforestation and Disruption of Hydrological Cycles

While forests act as engines sustaining atmospheric rivers and monsoon rainfall, deforestation disrupts these hydrological pathways, weakening moisture transport and destabilizing rainfall patterns critical for rice agriculture. Evidence from observational studies and model simulations shows that deforestation can diminish monsoon intensity, reroute atmospheric rivers, and disrupt seasonal cycles.

Tropics-wide Precipitation Declines

A multi-region study found that, across the tropics, for every 1% of forest lost, monthly precipitation reduced by 0.25 mm when analyzed at the largest scale (aggregated over 200 km areas). In the Congo Basin this equates to an 8–10% decline in annual mean rainfall by 2100. However, at smaller scales (<50 km), deforestation can sometimes produce short-lived increases in rainfall frequency due to thermally and dynamically induced circulations near forest edges, even though the net regional effect remains negative (Smith *et al.*, 2023).

Figures 4a/b show the relation between projected forest cover lost and change in precipitation across the tropics. Associated rainfall declines closely mirror the trajectory of forest loss, with the Congo facing the sharpest reductions. Furthermore, spatial patterns (Figures 4c/d) show that deforestation hotspots in the Amazon, Congo, and Southeast Asia closely align with areas of greatest rainfall loss, highlighting the exposure of major rice-producing regions to disrupted hydrological cycles. Because rice cultivation depends on predictable wet-season rainfall to establish crops and on consistent irrigation recharge to sustain them, any weakening or rerouting of precipitation threatens planting schedules, water security, and ultimately yield stability.

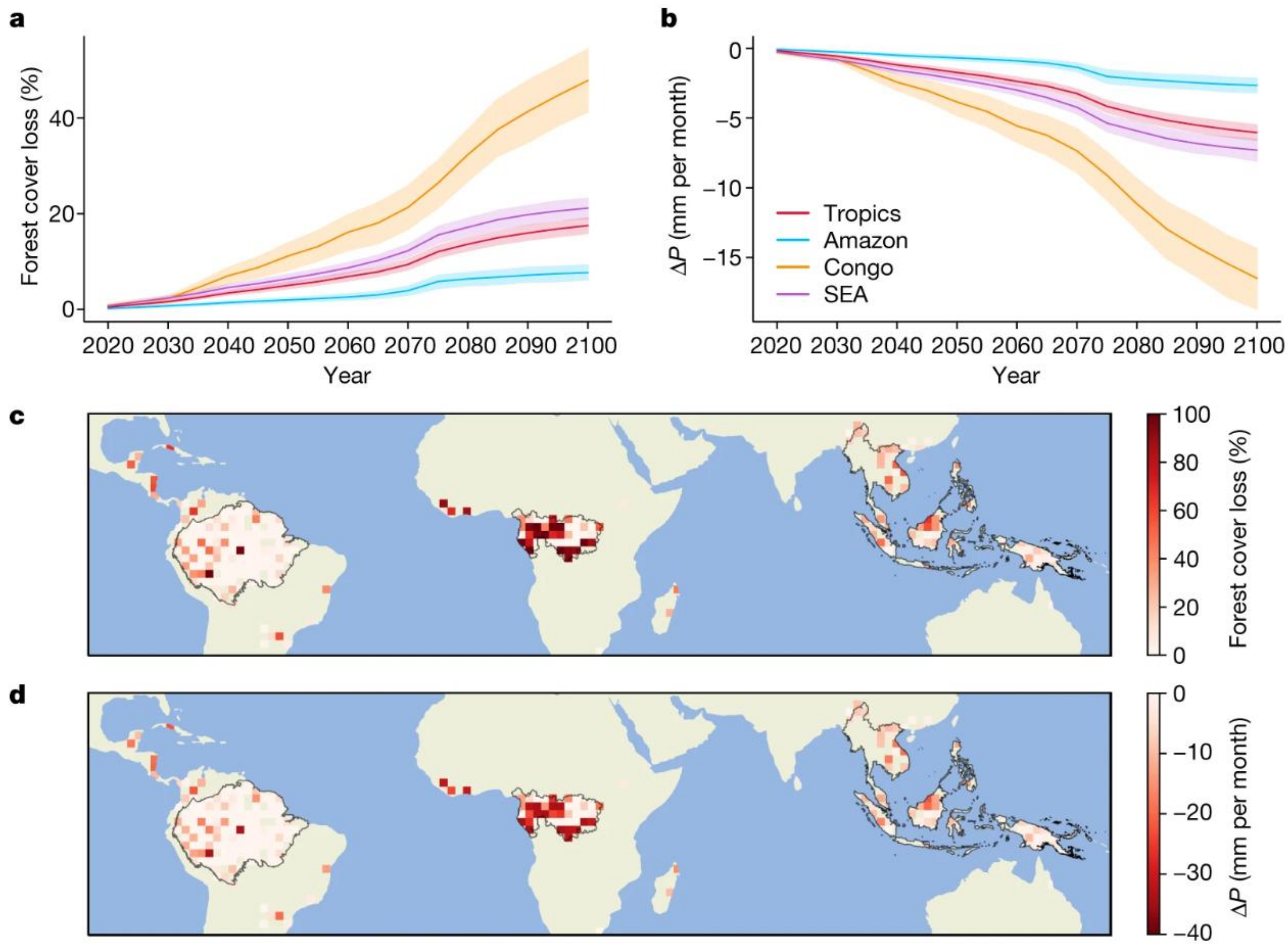

Figure 4: Projected effects of tropical deforestation on rainfall: (a) forest-cover loss, 2020–2100; (b) change in monthly precipitation; (c) forest-loss hotspots; (d) precipitation change in 2100. Source: Smith et al. (2023), CC BY 4.0

Weaker Monsoons from Land Use & Land Cover Change (LULCC)

In addition to rainfall reductions observed across scales, further modelling work demonstrates the link between land-use and land-cover change and the weakening of monsoon systems, essential for rice systems.

Quesada *et al*. (2017) used five coupled global climate models (GCMs) under the RCP8.5 emissions pathway to isolate the biophysical effects of LULCC on future rainfall. Their simulations show that while global warming tends to intensify monsoon rainfall, deforestation and cropland expansion offset part of this increase, reducing projected monsoon precipitation by roughly 9 % in India and 12 % in East Asia, and by even more in other regions. These findings indicate that LULCC can substantially weaken the intensity, duration, and spatial extent of monsoon rains, even as total global precipitation increases under a warmer climate. These findings have direct implications for rice production, as India and East Asia together account for the largest share of global rice cultivation. In regions like South Asia and the Mekong Basin, where food security depends heavily on the timing and volume of monsoon rainfall, the projected weakening from LULCC represents a major vulnerability. Protecting forest cover in upland catchments is therefore critical, not only for sustaining atmospheric rivers but also for maintaining the strength of monsoon systems that underpin rice agriculture.

Global Teleconnection Impacts

Beyond regional and monsoon-scale effects, modelling studies also demonstrate that deforestation can alter rainfall thousands of kilometers away by rerouting large-scale atmospheric circulation. Demonstrating the global reach of ecoclimate teleconnections.

Avissar and Werth (2005) used GCM ensembles to test the effects of large-scale forest clearance in the Amazon, Central Africa, and Southeast Asia (SEA). Their simulations

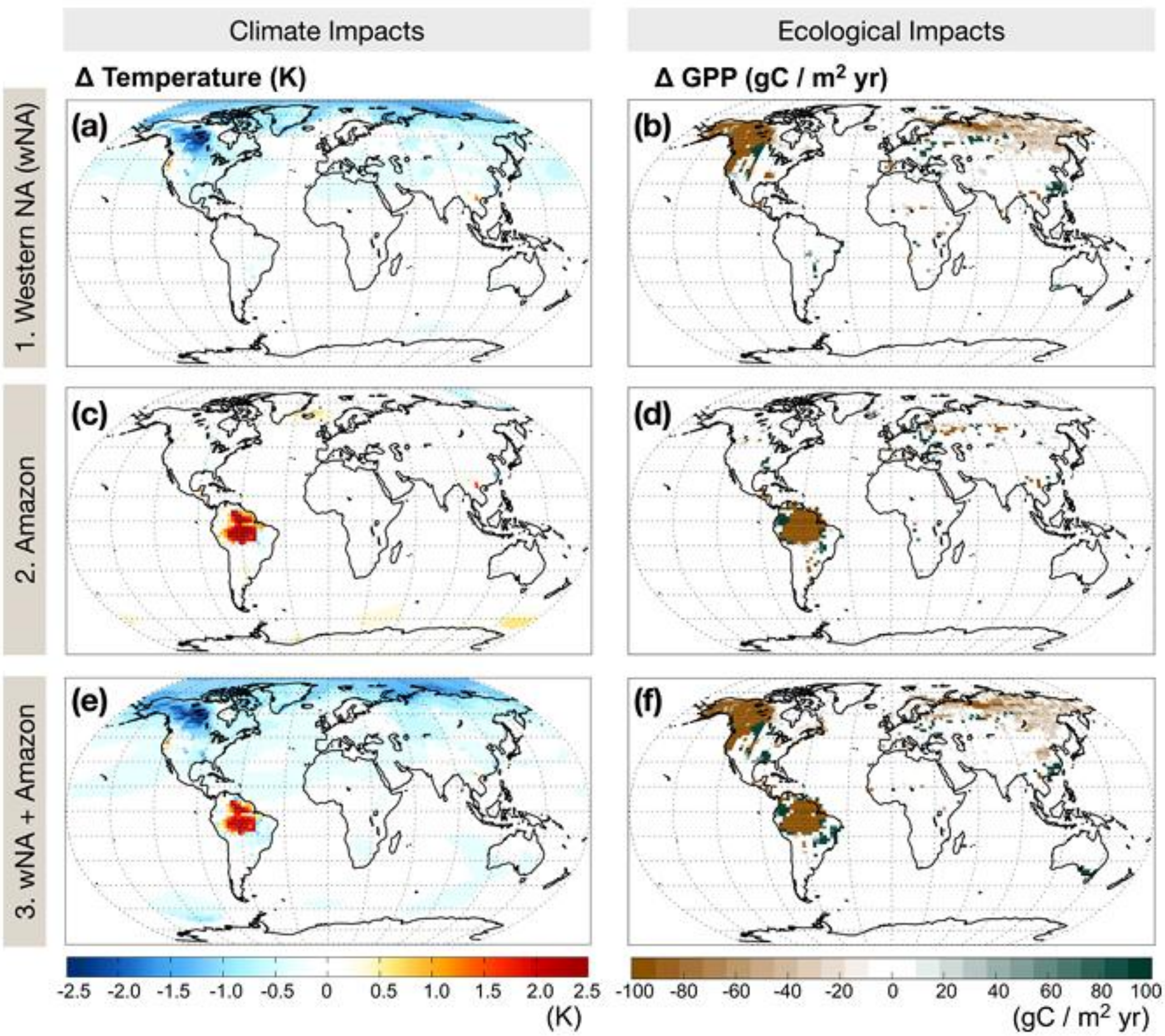

Figure 5: (a, c, e) anomalies in temperature (K); (b, d, f) anomalies in gross primary productivity (gC m $^{-2}$ yr $^{-1}$), Climatic and ecological responses to Amazon and western North America forest loss. Source: Garcia et al. (2016). Licensed under CC BY 4.0.

showed that Amazon deforestation reduced local wet-season rainfall by 50–60% and triggered a 25% decline in spring–summer precipitation in the US Midwest, while even increasing rainfall in some distant arid zones such as the Arabian Peninsula (+45%).

Similarly, Medvigy *et al*. (2013) found that complete Amazon deforestation reduced winter precipitation across western North America by 10–20% (1–2 mm day^{-1}). Garcia *et al*. (2016) extended this line of evidence by examining how deforestation alters the position of the Intertropical Convergence Zone (ITCZ). The results showed that forest loss in both the Amazon and western North America produced a southward displacement of the ITCZ, causing drying in the Northern Tropics (0.05 mm day^{-1}). At the same time, rainfall increased in some parts of the southern tropics, reflecting a redistribution, rather than total decline. Together these studies demonstrate that forest loss does not only diminish local rainfall but can also reroute atmospheric circulation, shifting rainfall belts across continents.

This is further illustrated by global modelling evidence (Figure 5), which shows both the climatic and ecological consequences of Amazon and western North America (wNA) deforestation. Panels (a, c, e) highlight how forest loss alters temperature patterns, reinforcing the hydrological shifts described by Garcia et al. (2016), while panels (b, d, f) demonstrate concurrent declines in gross primary productivity (GPP) across distant ecosystems. In particular, the Amazon–wNA combined experiment reveals that forest loss propagates productivity losses into regions far beyond the tropics. Reductions in GPP matter not only for global carbon balances but also for the ecological foundations of agriculture, including rice systems, which depend on stable rainfall and fertile, productive landscapes.

Although these experiments were focused on the Americas, the principle is highly relevant for rice systems. They provide proof of concept that deforestation can disrupt moisture flows thousands of kilometers away, not just in adjacent landscapes. Consequently, protecting tropical forests is a global food security issue: forest conservation in one continent safeguards rainfall in another, and in doing so helps to maintain the hydrological reliability that rice farmers depend on.

Southeast Asia Hydrological Shifts

Regional-scale evidence in Southeast Asia further illustrates with a stylized experiment of complete deforestation how changes in forest cover can fundamentally alter local water balances and shift dependence from recycled to imported rainfall.

Using the COSMOS general circulation model, Schneck and Mosbrugger (2011) simulated the complete deforestation of Southeast Asia to explore its regional hydrological consequence. Their results showed that evapotranspiration collapsed by –367 mm yr^{-1} (–32%), leading to a corresponding decline in local rainfall of –154 mm yr^{-1} (–11%). Interestingly, at the same time, atmospheric moisture convergence into the region intensified sharply by +213 mm yr^{-1} (+118%). In other words, reduced evapotranspiration warms the land surface relative to adjacent oceans, creating stronger low-pressure gradients that pulled in external moisture. Therefore, moisture builds up in the air, but fails to translate into precipitation, because without trees driving evapotranspiration, cloud formation is suppressed.

For rice systems in Southeast Asia, this hydrological shift poses a serious vulnerability. Once forests are removed, basins such as the Mekong, Chao Phraya, and Red River must rely increasingly on imported atmospheric moisture instead of much reduced local recycling.

Climate-Context Differences

The impacts of deforestation also vary with climatic setting, as demonstrated by Knox *et al*. (2015), who showed that the same forest loss can trigger opposite rainfall responses in semi-arid and humid zones.

They examined how deforestation affects rainfall under different climatic settings by coupling a terrestrial ecosystems model (ED2) with a regional atmosphere model (BRAMS). Their simulations compared responses in semi-arid and humid tropical regions of South America. In the semi-arid Gran Chaco, evapotranspiration fell by 29 mm, but moisture convergence intensified (–15.5kg m^{-2}), suggesting enhanced inflow. By contrast, in humid Pará, evapotranspiration dropped by 32 mm and convergence weakened (+14.2 kg m^{-2}), producing overall drying. For rice systems concentrated in humid tropical basins such as the Mekong and Ganges, this points to a clear risk: deforestation in these settings reliably reduces rainfall, while outcomes in semi-arid areas remain less predictable. This underscores the need for regionally tailored watershed conservation strategies to safeguard atmospheric-river supply into rice basins.

Afforestation vs Deforestation Contrasts

At the scale of the entire Asian monsoon domain, Dallmeyer and Claussen (2011) show how land-cover change affects both local rainfall and remote teleconnections as far as the Sahara and the Middle East. They found that deforesting the Asian monsoon region (see Fig. 6) caused local rainfall declines of up to –2.3 mm day^{-1} in core rice-growing areas such as the Yangtze–Huanghe plain and Bay of Bengal rim, while more than doubling summer rains in parts of the Sahara. By contrast, afforestation enhanced local monsoon rains in Tibet and Northeast China (+0.77 mm day^{-1}) but reduced them in South India and the Yangtze Delta (–0.43 mm day^{-1}) and even suppressed Middle Eastern summer rainfall by up to 100%.

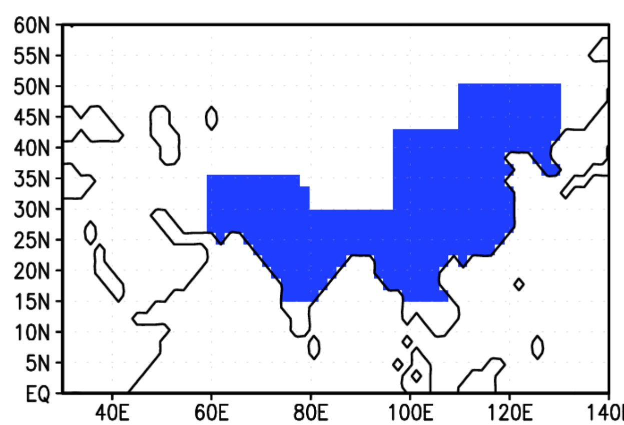

Figure 6: Asian monsoon region (Blue). Source: Dallmeyer & Claussen (2011), Biogeosciences, 8, 1499–1519 (CC BY 3.0).

These results highlight the bidirectional consequences of upland land-cover change: while deforestation starves Asian rice basins of monsoon water, it can enhance rainfall in arid zones, whereas afforestation strengthens local recycling but may deprive remote regions of moisture. For rice systems, these results underscore that forest management in Asia is not just a local concern: deforestation can strip water from monsoon-dependent rice basins, while afforestation may enhance local rainfall but disrupt remote atmospheric-river pathways, creating complex trade-offs for agricultural water security.

2.5 Implications for Rice Landscapes

Protecting forests is critical for rice agriculture because their evapotranspiration seeds atmospheric rivers, stabilizes monsoon rainfall, and replenishes irrigation inflows. When cleared, several processes are affected: local water recycling collapses, rainfall becomes less reliable, and the atmospheric rivers that deliver moisture to rice basins are disrupted. The evidence shows that impacts vary with scale and context - each 1% of forest loss reduces rainfall by 0.25 mm per month in the tropics, with Congo-like declines of 8–10% projected by 2100; land-use change weakens Indian and East Asian monsoons by 9–12%; and global teleconnections demonstrate that deforestation in the Amazon can alter rainfall thousands of kilometers away. In Southeast Asia, experiments show that even as atmospheric moisture convergence increases after deforestation, rainfall still declines, leaving deltas like the Mekong dependent on erratic imports rather than stable local recycling. Context-specific studies further reveal that humid rice basins are especially vulnerable, as deforestation usually reduces rainfall, while afforestation can enhance local water recycling but disrupt remote rainfall pathways. Taken together, these findings frame forests as indispensable “green infrastructure” for rice landscapes: conserving them helps secure rainfall, irrigation flows, and yield stability, while their loss heightens vulnerability to drought, delayed planting, and harvest failures.

3. Forests and the Terrestrial Water Cycle

While forests shape rainfall patterns through their influence on atmospheric moisture flows, their most immediate contribution to the nature–climate–food nexus lies in regulating the terrestrial water cycle. Through canopy interception, controlling runoff, infiltration, subsurface flow, and recharge, forests govern how rainfall is stored, released, and redistributed across landscapes. Forest root systems and organic-rich soils enhance infiltration, reduce surface runoff, and stabilize slopes, reducing flood peaks and landslide risk during monsoon seasons. The water absorbed by these ecosystems replenishes groundwater and sustains baseflows that feed rivers, wetlands, and irrigation systems throughout the dry season. As groundwater extraction and land-use change intensify, these forest-mediated hydrological functions have become essential natural infrastructure for sustaining both ecosystems and rice production across Asia's monsoon landscapes.

3.1 Forest Infiltration and flood reduction

Infiltration, the entry of rainfall into the soil, is central to the green water cycle. Land-use change alters soil structure and hydraulic properties (bulk density, macroporosity, saturated hydraulic conductivity), thereby modifying infiltration capacity (Sun *et al.*, 2018).

In Nepal's Middle Mountains, monsoonal overland-flow totals were about 2.5% under natural forest versus 15.5% in heavily used pine and 21.3% on degraded pasture (Ghimire et al., 2013). Greater overland flow on degraded slopes translates into sharper, faster flood peaks and lower rainfall needed to trigger landslides. While questions remain over a simple link between deforestation and flooding at large basin scales, many studies document consistent event-scale and headwater (more local) effects. Analyses by van Noordwijk et al. (2017) show that when flow persistence (Fp) declines, rivers become more "flashy" and storm peaks grow. Fp is the fraction of today's flow that can be explained by yesterday's flow (between 0 and 1). Vegetation loss and soil degradation lower Fp by shifting gradual infiltration and subsurface flow toward faster overland runoff, reducing the catchment's capacity to blunt floods (Van Noordwijk et al., 2017).

Figure 7 illustrates this shift as Fp falls, a smooth, storage-dominated hydrograph gives way to tall, spiky peaks - i.e., a "flashier" river. Quantitatively, once Fp falls below 0.5 there is <10% flood-peak reduction left over 1–5-day events, meaning a degraded catchment is functionally no longer blunting storms.

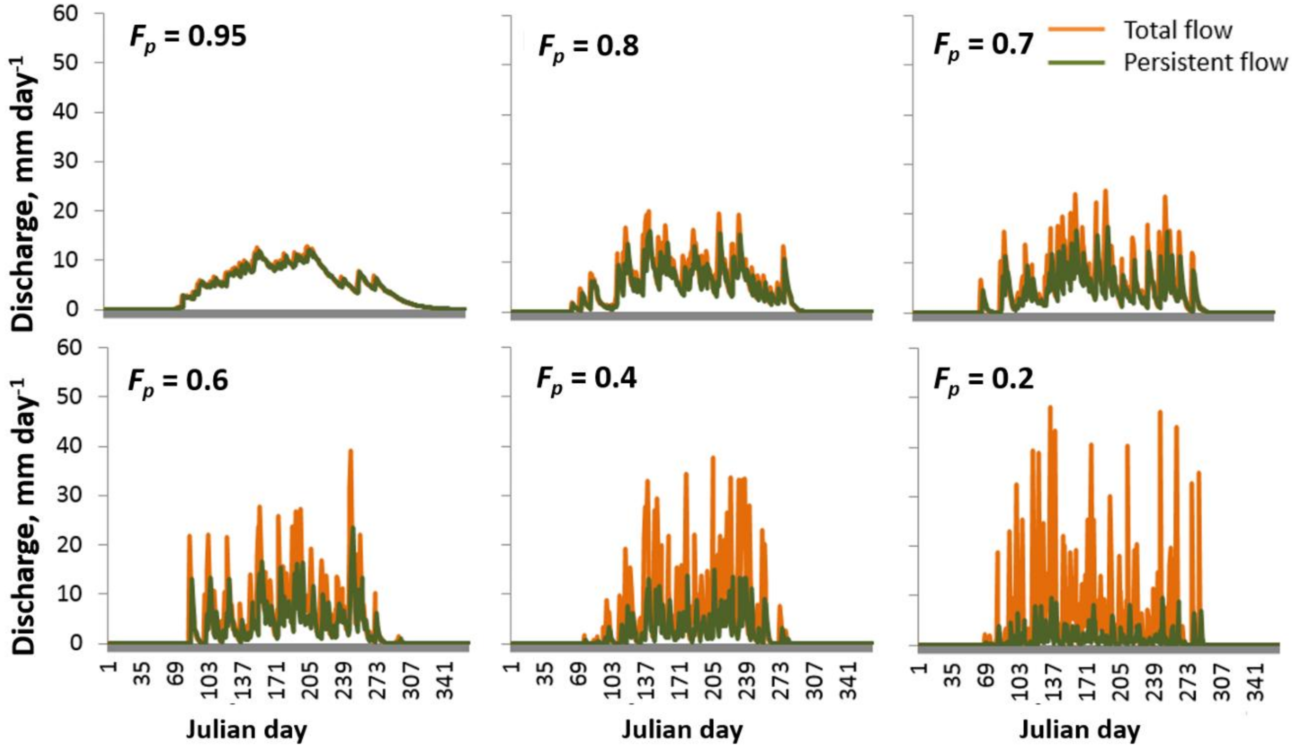

Figure 7: Simulated daily discharge for catchments with different flow persistence (Fp) value. Source: van Noordwijk et al. (2017). Licensed CC BY 3.0.

In practice, these effects are clearest in headwaters (small basins with little storage), yet at larger scales the signal can be diluted by floodplains, reservoirs, and asynchronous rainfall, even though the event-scale mechanism remains the same. For instance, in Côte d'Ivoire, runoff fractions fall from 30–50% at 1 m^2 micro-plots to 4% at a 130 ha basin, as storage and infiltration increase as with scale, buffering the impact over space and time (Van de Giesen et al., 2000). These findings show the benefits that intact, healthy upland forests provide – improving infiltration, buffering event peaks, and ultimately stabilizing slopes – reducing the chances of damaging events such as floods and landslides.

3.2 Recharge, Baseflow and Depletion Risk

Intact upland forests promote percolation and route runoff toward slower pathways that sustain baseflows. In a mountainous Beijing catchment, broadleaf/mixed forests routed about 60% of runoff as baseflow (interflow and groundwater), higher than conifer and shrub types, while increasing forest cover was found to raise the baseflow share (Ding et al., 2022). Across the seasonally dry tropics, groundwater recharge is maximized at intermediate tree cover: too sparse tree cover reduces infiltration, while too dense allows for evapotranspiration to take over (Ilstedt et al., 2016).

In rice dominated areas, human water management reshapes these pathways. Process-based SPHY simulations in the

Central Indian Highlands show that raising forest cover to 33% reduces recharge (about 1%) if trees replace paddy (which already provides depression storage and continuous percolation) but increases recharge (by about 3%) if reforestation targets non-paddy uplands (Clark et al., 2021). Bunded paddies already act as seasonal recharge basins converting them to trees raises interception/ET and shortens ponding, reducing recharge. Reforesting non-paddy uplands, riparian strips, and gullies instead boosts infiltration, slows fast runoff, and yields modest gains in recharge and peak-flow buffering without sacrificing paddy-driven managed aquifer recharge (MAR).

From a global perspective, coupled models show that even modest groundwater-level declines from pumping can sharply reduce groundwater discharge to rivers, breaching environmental-flow limits – already in 15–21% of pumped basins and projected to reach 42–79% by 2050. Crucially, stream impacts often occur before large aquifer depletion and can be delayed by months to decades, reinforcing the need for conjunctive management (protecting recharge, maintaining MAR, and enforcing demand rules) to secure dry-season baseflows (de Graaf et al., 2019).

4. Local Forest–Rice Interactions: Agroforestry and Green Water

On a regional scale, forests regulate rainfall delivery through atmospheric rivers and monsoon systems, however, the trees embedded within rice landscapes shape how that water is captured and used on the ground. Exploring the relation between forests and rice farming at a local scale gives us a clearer idea of the potential benefits they can have for each other. Beyond water regulation, trees also underpin other services such as pest control and soil fertility (explored in more detail later). Agroforestry explores these local connections.

Agroforestry is the intentional integration of trees into rice-based systems. It represents a long-standing but increasingly vital adaptation strategy for smallholder farmers. These systems take many forms: scattered trees within paddies, shelterbelts along field margins, or tree-lined bunds that both delineate plots and provide ecological services. The choice of species reflects a balance between soil fertility, microclimate regulation, and resource provision. Nitrogen-fixing species are particularly valued. For example, *Sesbania rostrata* used as a green manure in lowland rice systems can contribute substantial nitrogen inputs, often exceeding 100 kg N ha^{-1} within a single season, thereby reducing fertilizer requirements and improving long-term soil fertility (Ladha, Miyan & Garcia, 1989).

Evidence from a meta-analysis of 33 paired trials across Asia and Africa shows the broader benefits. In unfertilized paddies, tree integration boosted yields by an average of +38%, while in low-yield but fertilized fields it added +23%. Yet poorly managed competition reduced yields by –12% on average. Practices that minimize competition, such as green manure biomass transfer (+1 500 kg ha^{-1}) or

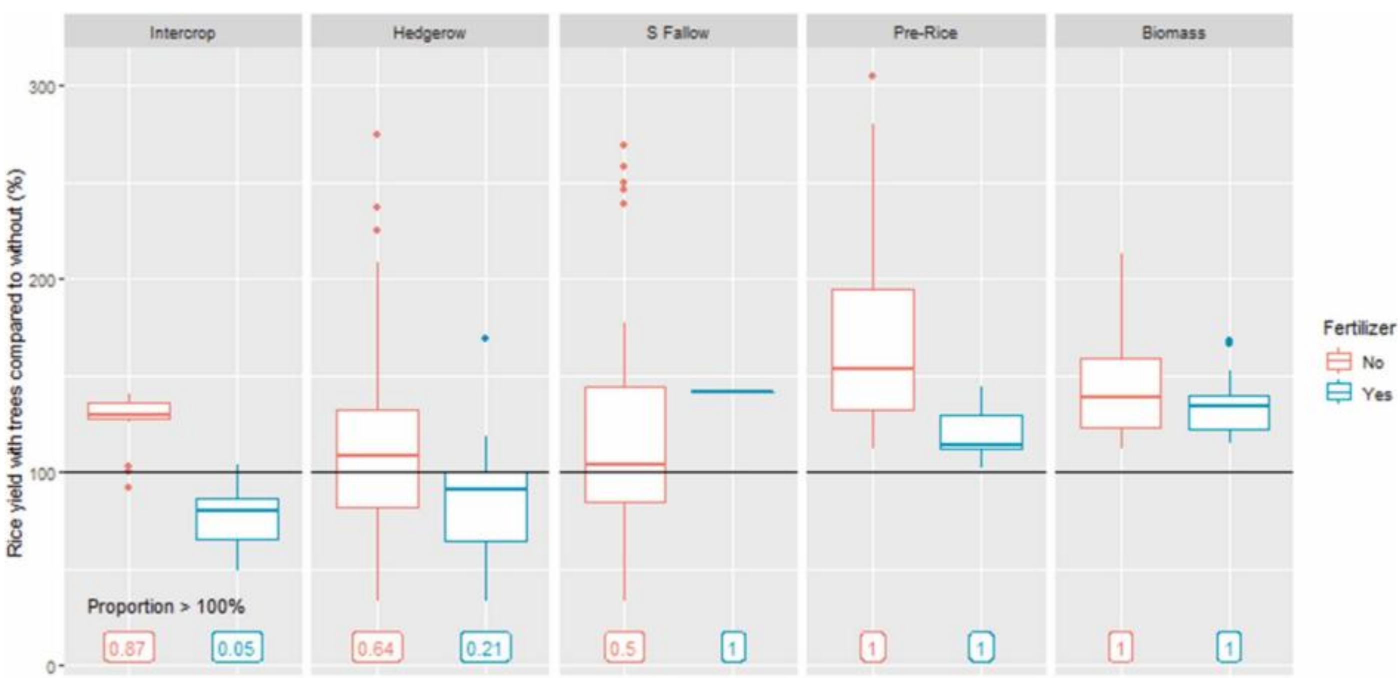

Figure 8: Effects of agroforestry practices on rice yields with and without fertilizer, showing synergies between tree-based systems and nutrient use efficiency. Source: Rodenburg et al, (2022). Licensed under CC BY-NC-ND 4.0

pre-rice pruning (+1 100 kg ha^{-1}), delivered the most consistent benefits (Rodenburg *et al.*, 2022).

This is illustrated in Figure 8, which depicts yield responses to different agroforestry practices with and without fertilizer. The figure shows that benefits are not evenly distributed across practices: while biomass transfer and pre-rice pruning consistently enhance yields, others such as intercropping or hedgerows produce mixed results, highlighting the importance of tailoring agroforestry design to local conditions and management.

Further case studies illustrate these synergies. In northeast India, the use of *Erythrina indica* green manure raised yields by 69% over unfertilized plots, while also improving soil carbon and nitrogen levels (Tomar *et al.*, 2012). On Hainan Island, *Bombax ceiba* trees created nutrient "hotspots," enriching soils with K, N, and organic matter, and accounting for over 20% of microbial community variation, evidence that trees actively shape soil microbiomes (Wang *et al.*, 2022).

Together, these examples demonstrate that while regional forests secure the delivery of rainfall, on-farm trees determine how effectively that water is captured, cycled, and translated into productivity. Agroforestry thus represents a practical form of agroecological intensification – rebuilding fertility, stabilizing microclimates, and strengthening resilience to climate stress. However, these systems can be labor-intensive and require careful management to avoid disservices, underlining the need for supportive policies and farmer incentives (Wezel *et al.*, 2020).

5. Biodiversity and Microbiomes

Just as forests and agroforestry systems regulate the flows of water and nutrients across landscapes, biodiversity at multiple scales sustains the productivity and resilience of rice agroecosystems. Biodiversity operates visibly, through birds, fish, insects, and cropping diversity, but also invisibly, through microbial communities in soils and waters that recycle nutrients and regulate greenhouse gases. Together, these layers of biodiversity underpin the nature–climate–food nexus.

Figure 9: White Stork (Ciconia), photographed in Kruger National Park, South Africa. Photo by Bernard Dupont, licensed under CC BY-SA 2.0 via Wikimedia Commons

5.1 Biodiversity in Rice Ecosystems

Biodiversity in rice landscapes arises from how water is held and moved: ponded fields that act as substitute wetlands, vegetated margins and canals that provide habitat and natural pest control, and deliberate species integrations (e.g., rice–fish/shrimp) that recycle nutrients and can raise yields, together sustaining productivity and resilience.

Rice as Substitute Wetlands

Rice paddies, when managed under flooded conditions, can partially mimic wetland habitats and provide refuge for aquatic and avian species. In a two-year survey, Paulino *et al*. (2024) recorded 52 species of waterbirds in rice fields, nearly as many as adjacent lakes (53) and far exceeding pastures (14). The study also found that 97% of White Stork sightings occurred in rice fields, underscoring their role as critical foraging sites.

Similarly, Lourenço and Piersma (2009) observed flooded paddies in central Portugal supporting on average 4.07 birds/ha, closely matching nearby estuarine wetlands (4.72 birds/ha). When paddies were inundated, Black-tailed Godwit densities surged from 0 to 85.8 birds/10 ha, demonstrating that simple water management such as post-harvest flooding, recreate foraging habitats equivalent to natural wetlands.

However, biodiversity gains are not uniform. In Spain's Ebro Delta, seasonally flooded rice paddies harbored just 9 of 19 native fish species found in the wider irrigation network, with native fauna making up fewer than 5% of 614 total captures, and average native species richness were eight times lower than that of introduced species (Clavero *et al*., 2009). This highlights how habitat simplification through monoculture can reduce overall biodiversity, even when paddies superficially resemble wetlands.

Habitat Provision and Pest Control

Beyond their role as wetlands, rice fields can also enhance biodiversity through on-farm habitat features. Vegetative strips, hedgerows, canals, and farm ponds provide shelter for predators of rice pests, such as spiders, dragonflies, and fish. Studies in Southeast Asia show that maintaining such habitat diversity increases predator abundance and reduces outbreaks of pests like the brown planthopper (see figure 10) (Ali *et al*., 2023). By sustaining natural enemies, farmers can lower pesticide use, which improves environmental and farmer health, cuts costs, and provides more sustainable yield protection.

Figure 10: Brown Planthopper (Nilaparvata lugens) adults on rice stems. Source: LucidCentral Pest and Disease Image Library (2023)

Agrobiodiversity in Practice

Agrobiodiversity - the intentional integration of multiple species into farming systems – can also generate biodiversity gains. Two well-documented examples are the rice–shrimp systems of the Mekong Delta and the Ifugao rice terraces in the Philippines.

Rice–shrimp systems in the Mekong: In brackish delta regions, farmers alternate rice during the wet season with shrimp in the dry season. This coupled agro-aquatic system recycles nutrients, reduces fertilizer dependence, and diversifies incomes. Rice plants filter and oxygenate water, shrimp burrowing aerates sediments and stimulates microbial activity, while shrimp excretion returns bioavailable nitrogen and phosphorus to the soil. Empirical studies show these systems maintaining high water quality, with a five-day biological oxygen demand (BOD) of about 3.3 milligrams per liter and dissolved oxygen levels between 6.3 and 8 milligrams per liter, conditions reflecting low organic pollution and healthy aquatic environments (Chowdhury *et al*. 2011).

Comparative evidence shows that integrating aquatic species into rice systems tends to enhance rice yields. In Bangladesh, rice–fish systems produced 4.7–5.3 t/ha of rice, slightly higher than the 4.2–4.7 t/ha achieved in conventional rice-only systems without fish (Table 1) (Ibrahim et al, 2023). Similarly, in China, rice-shrimp and rice-fish systems yielded 8.3–12.0 t/ha, compared to 7.9–10.3 t/ha in rice-only fields. The evidence suggests that Rice–Aquatic Species Integration Systems (RASp) represent a viable pathway to sustain, and in many cases, improve rice yields while diversifying production, while reducing reliance on external inputs and lowering nutrient and pesticide loads to surrounding waters. Furthermore, productivity data reports that alongside the 2.0–3.0 t ha^{-1} of rice, farmers also harvested 50–80 kg ha^{-1} of cultured shrimp and 150–200 kg ha^{-1} of wild-capture fish (Ibrahim *et al*, 2023). These systems exemplify how agrobiodiversity can sustain environmental functions such as nutrient recycling and water quality, while simultaneously diversifying farmer livelihoods and income.

Table 1: Comparative productivity of rice monoculture and rice–aquatic species integration systems across selected countries. Source: Ibrahim et al, (2023). Licensed under CC BY 4.0.

	Productivity (kg/ha/Season)			Fish Species
	Rice Mono-	Fish	Rice	
Bangladesh	4702	259	5261	*C. carpio, B. gonionotus, O. niloticus*
	4188	485	4736	
	-	1453	2257	*Prawn & fish*
	-	827	2352	
	-	1080	3800–5000	*B. gonionotus, O. niloticus*
Indonesia	-	300–890	6380–7780	*C. carpio, B. gonionotus*
China	7915–10,319	1900–2500	8300–12,000	*C. carpio, B. gonionotus*
		372	6290	*C. carpio var. color*
India	5560	1230	5800	*Rohu, Catla, Silver carp, Common carp, & Mrigal*
	-	1144	3300	*C. catla, C. carpio, C. mrigala, L. rohita*
	3362	980	3629	*C. catla, L. rohita, C. mrigala, C. carpio & M. rosenbergii*
	-	1300–2000	3000–3600	*B. gonionotus, C. catla, C. mrigala*
Ghana	-	201	4410	Nile tilapia (*O. niloticus*)
Vietnam	-	325–1218	2182	Mud Carp, Chub, Carp
	-	1024–2200	5700–6806	*C. carpio, B. gonionotus, O. niloticus*
	-	326	4209	
Thailand	-	173	363	
	-	900–1100	-	
	4700	300	3600	*O. niloticus, C. striata, C. carpio, B. gonionotus, C. cirrhosus, P. jullieni, C. batrachus*
Japan	4061–5319	345	4871–6381	*Carassius* complex, Goldfish
Nepal	3370	354	3670	Common carp (*C. carpio*)

The Ifugao terraces in the Philippines, a UNESCO World Heritage site, have long been celebrated as a cultural landscape where agriculture, biodiversity, and community practices are tightly interwoven. Historically, paddies and canals supported a diverse array of aquatic species, including native snails such as *Jagora asperata* (*agurong*), edible mollusks (*bisukol*), crabs, fish, and frogs, which formed part of local diets and agroecosystem functioning. Surveys in Asipulo, Ifugao, recorded *Jagora asperata* at around 30 individuals/m^2, highlighting the abundance of native species in these traditional rice systems. These aquatic organisms provide vital protein for households and contribute to nutrient cycling, underscoring the terraces' role as productive rice landscape and a reservoir of agrobiodiversity. However, the biodiversity that has historically supported the productivity and resilience of the terraces is now increasingly under threat. Farmer testimonies identified pesticides, excessive collection, drought, and invasive species as the major drivers of decline (Ngidlo & Baguinon, 2014). This raises important questions about the long-term sustainability of rice systems under systems under changing ecological and management pressures.

Figure 11: Rice–fish farming in Sri Lanka. Source: AgriTech Insights LLC (2025)

5.2 Pressures on Biodiversity

While traditional rice landscapes have historically coexisted with diverse species, the drive for intensification has placed increasing strain on these ecological relationships. Large-scale infrastructure and wetland conversion within rice areas, together with forest clearance for plantations, tree crops, and other non-rice land uses, are simplifying landscapes. These changes may boost short-term production and profitability in some sectors, but they diminish the habitats and ecological functions that support wider biodiversity and many regulating services (such as flood buffering, water purification, and natural pest control). The following cases illustrate how these pressures are reshaping rice agroecosystems across Asia.

Migratory fish in the Mekong: In the Mekong Delta, the construction of high dikes for triple-cropping has blocked seasonal flood pulses that historically enabled fish to migrate, spawn, and feed in rice paddies. As a result, wild fish yields have declined by 68–83%, species diversity has fallen by 75–81%, and 94% of farmers reported water quality deteriorating from “good” to “poor” (Chau Thi Da *et al*, 2024). This illustrates how hydraulic infrastructure designed to maximize rice yields simultaneously undermines fisheries that once provided protein, nutrient cycling, and income to farming households.

Sarus Cranes in South Asia: Across the Indo-Gangetic plains, wetland conversion into rice has displaced migratory birds such as the Sarus Crane. In Gujarat, India, 97.1% of cranes preferred the few remaining marshland patches rather than rice paddies, and nest success in human-dominated landscapes fell to just 55% (Borad *et al*., 2001). Territories dominated by seasonal wetlands had brood survival rates of 59%, compared to 66–68% in areas with perennial wetlands and rice fields (Sundar, 2009). These findings show that rice-based intensification can fragment habitats and reduce reproductive success for wetland-dependent species.

Tigers in Asian forests: In lowland India, Bangladesh, and Indonesia, forest clearance for agriculture, including rice, has sharply contracted the range of the tiger. Tigers now occupy only 7% of their historic range, and between 1997 and 2007 their habitat contracted by a further 41% (Dinerstein *et al.*, 2007). The conversion of natural wetlands and forests to rice paddies, alongside roads and canals, fragments landscapes and isolates wildlife populations, reducing both biodiversity and the broader ecological functions that forests provide.

Together, these cases reveal a consistent pattern: the very measures used to intensify rice production, from high dikes to wetland drainage and forest clearance, simplify landscapes while eroding the biodiversity that sustains them. The declines of fish, cranes, and tigers are not just isolated conservation concerns, but indicators of wider ecological disruption, including weakened nutrient flows, reduced hydrological buffering, and loss of habitat connectivity.

5.3 Invisible Biodiversity: Microbiomes

Beyond visible biodiversity such as fish, birds, and large mammals, rice systems also depend on a hidden layer of life: the microbial communities that thrive in their soils and flooded waters. These microorganisms (bacteria, fungi, archaea, and protists) underpin key ecological processes that directly shape rice productivity and its climate footprint. Yet, like larger organisms, they are highly sensitive to how fields and landscapes are managed.

Nutrient Cycling

Microbiomes play a central role in nutrient dynamics within rice paddies. Microbial communities underpin the nutrient economy of rice paddies by fixing atmospheric nitrogen, decomposing residues into organic matter, and solubilizing bound phosphorus. These processes sustain soil fertility and reduce reliance on external inputs, allowing rice systems to recycle nutrients internally. For instance, under flooded conditions, iron-reducing microbes such as *Geobacter* convert straw-derived carbon while simultaneously fixing nitrogen. This process can be further stimulated by iron amendments, which have been shown to increase fixation rates up to three to four times in unfertilized plots (Zhang *et al*., 2023). Such findings highlight how microbiomes provide essential fertility services that can be enhanced by ecological management, in contrast to the soil degradation often associated with heavy fertilizer use.

Climate Regulation

Microbial activity also shapes the climate footprint of rice cultivation. In flooded soils, methanogenic archaea thrive under anaerobic conditions and generate methane (CH_4), making rice paddies one of the largest agricultural sources of this greenhouse gas, responsible for an estimated 11% of global anthropogenic CH_4 emissions (Xuan *et al.*, 2025). Other microbes, such as denitrifying bacteria, convert nitrate into nitrous oxide (N_2O), another potent greenhouse gas. The balance between these microbial processes depends strongly on how fields are managed. Herbicide trials in India showed that even recommended doses of pendimethalin and pretilachlor sharply reduced the abundance of core microbial groups, replacing them with unclassified taxa and eroding overall diversity (Bhardwaj *et al.*, 2024). By contrast, long-term fertilization experiments demonstrated that sustainable nutrient regimes maintained the highest microbial diversity and enzyme activity compared to conventional or unfertilized plots (Chen *et al.*, 2024). Moreover, Fan *et al.* (2016) found that combining fertilizer with straw reduced N_2O emissions relative to urea alone, while supporting microbial genes associated with N_2O reduction. These results underscore that microbial diversity and function are central levers for shaping the climate footprint of rice systems.

Land-use change

Pressures on microbiomes also extend beyond the field. Deforestation and the conversion of tropical forests to agriculture or plantations consistently depress the abundance and functioning of key soil microbial groups. A global meta-analysis of 83 paired sites found that microbial biomass carbon and nitrogen both declined significantly following forest-to-agriculture conversion, while bacterial and fungal abundances were also reduced. Enzyme activities linked to litter decomposition and nutrient release likewise weakened, implying slower nutrient cycling and reduced fertility under deforested land uses (Díaz-Vallejo *et al.*, 2021). For rice-based systems, this means that clearing upstream

Figure 12: Deforestation in Tasman, New Zealand. Photo by Martin Wegmann, licensed under CC BY-SA 3.0 via Wikimedia Commons.

forests and wetlands not only alters hydrology but also cuts off organic matter inputs, diminishing the microbial processes that sustain soil health. Over time, such changes increase farmers' reliance on synthetic fertilizers and erode the resilience of agroecosystems at the heart of the nature–climate–food nexus.

Microbial communities are not passive background biodiversity but active regulators of fertility, resilience, and greenhouse gas emissions. Their functioning is shaped by management decisions - from fertilizer use and herbicide application to straw incorporation and land-use change. Sustaining microbial diversity is therefore not simply a conservation concern but a cornerstone of building productive, resilient, and climate-compatible rice systems within the nature–climate–food nexus.

Protecting biodiversity at all scales is therefore not an optional conservation add-on, but an essential condition for sustaining yields, reducing dependence on external inputs, and mitigating climate risks. This makes biodiversity central to the long-term viability of rice agriculture. Safeguarding biodiversity and soil microbiomes are as much about food security, resilience, and climate action as it is about conservation. Integrating biodiversity protection into agricultural policy and management strategies offers a pathway to align productivity goals with climate commitments and ecosystem health.

6. Ecosystem Services and Disservices

Rice agroecosystems generate a complex mix of benefits and costs for people and the environment. On one hand, they deliver vital ecosystem services such as water regulation, pest control, nutrient cycling, and carbon sequestration, which sustain productivity and resilience. These services can improve or stabilize rice yields and reduce the need for external inputs (MEA, 2005). On the other hand, rice cultivation also generates disservices, including greenhouse gas emissions, agrochemical runoff, and health risks from vector-borne diseases. The challenge is to move from input-intensive efforts to raise rice yields towards management that works with ecological processes, allowing water, soils and biodiversity to supply the supporting services needed for stable rice production and diversified incomes.

Table 2 highlights how the same rice landscape can simultaneously buffer against floods, host biodiversity, and support food webs, while also contributing to methane emissions or eutrophication. The balance between these services and disservices depends on management. Practices such as integrated pest management, alternate wetting and drying, and the conservation of adjacent forests and wetlands tend to enhance services and reduce disservices. By contrast, input-intensive rice systems amplify the negative externalities.

These dynamics are especially clear in coastal delta landscapes where rice interacts with mangroves and wetlands. In deltas such as the Mekong, Ganges–Brahmaputra–Meghna and Red River, low-lying, freshwater-rich plains have historically supported intensive rice production and dense populations, but are now under growing pressure from sea-level rise, salinity intrusion, subsidence and more frequent flooding. Here, the same ecosystems that provide nutrient flows, storm protection, and biodiversity habitat can also become sites of conflict when converted to intensive agriculture or aquaculture.

Table 2: Ecosystem services and disservices in forest–wetland–rice systems.

Function	Description	Outcome
Water Regulation (Service)	Forests/wetlands absorb peak flows, recharge groundwater, and stabilize baseflows.	Buffers rice paddies from drought and flood, ensuring more reliable water supply
Food and Fiber Provisioning (Service)	Rice paddies, wetlands and adjacent forests produce staple grains, fish, fodder, fuelwood and other biomass.	Provide calories, protein and key micronutrients, underpinning local food and nutrition security and supplying fiber and fuel for households.
Income and Livelihood (Service)	Higher-value crops, integrated rice–fish systems, non-timber forest products and related value chains generate marketable outputs and employment.	Increase and stabilize household cash incomes, buffer livelihood shocks, and create rural employment while maintaining stable rice production.
Pollination (Service)	Forests and grasslands host pollinators	Supports crop productivity and genetic diversity, boosting the availability of diverse, nutrient rich foods.
Pest Control (Service)	Birds, amphibians, and predatory insects suppress rice pests by feeding on larvae and insects.	Reduce pest outbreaks and lessen dependence on chemical pesticides.
Carbon Sequestration (Service)	Biomass and soils capture and store CO_2 over time through photosynthesis and organic matter accumulation	Mitigate climate change while improving long-term soil structure and fertility.
Soil Fertility (Service)	Nutrients are cycled via wetlands, flood sediments, and upland forest litter.	Maintain nutrient availability, improve soil fertility, and reduce external fertilizer demand.
Cultural and Recreational (Service)	Rice terraces, wetlands, sacred groves and flagship species hold cultural, spiritual, aesthetic and heritage value; some sites attract visitors for tourism, education and birdwatching.	Strengthen cultural identity and sense of place, support mental well-being, and generate tourism and recreation revenues for local communities.
Reciprocal Support (Service)	Well-managed rice fields function as seasonal wetlands, supporting water cycles and biodiversity.	Provide habitat for waterbirds, amphibians, and fish; regulate local hydrology and nutrient flows.
GHG Emissions (Disservice)	Flooded paddies emit methane (CH_4) and nitrous oxide (N_2O).	Amplify climate change through potent greenhouse gases and short-lived climate pollutants.
Agrochemical Runoff (Disservice)	Excess fertilizers and pesticides leach into rivers and canals, altering nutrient balances.	Trigger eutrophication, degrade aquatic habitats, and harm fisheries.
Air Pollution (Disservice)	Straw burning produces smoke, fine particulates, and toxic compounds.	Deteriorates air quality, harms human respiratory health, and contributes to regional haze.
Disease Vectors (Disservice)	Standing water creates breeding grounds for mosquitoes and snails that host parasites.	Increase risks of malaria, dengue, and schistosomiasis in farming communities.

7. Mangroves and Coastal Rice Landscapes

Mangroves form a critical coastal buffer in many rice-growing deltas of South and Southeast Asia, where paddy fields and aquaculture ponds often sit directly behind mangrove belts. Globally, mangroves are found in 128 countries, fringing nearly 15% of the world's coastlines, with over 30% of all mangrove area located in Southeast Asia (Rhodes, 2025). Their dense roots and above-ground structure dissipate wave energy, reduce storm surges, and stabilize soils, protecting both communities and rice production from coastal hazards. At the same time, mangroves sustain livelihoods by supporting fisheries, providing forest products, and recycling nutrients that flow into adjacent agricultural systems. Beyond these local functions, they also regulate climate through carbon storage and greenhouse gas mitigation. In this way, mangroves exemplify the multifunctional ecosystems at the heart of the nature–climate–food nexus: protecting rice systems from shocks, sustaining productivity, and delivering global environmental benefits.

Figure 13: Mangrove roots in Indonesia, showing dense root structures that stabilize coastlines and support biodiversity (Furnival, 2014; CIFOR)

7.1 Storm protection

Among the many services mangroves deliver, their role in protecting coastal rice landscapes from cyclones and storm surges is the most visible and well-documented. Their dense root and canopy structures dissipate wave energy, reduce wind speed, and stabilize soils, lowering the vulnerability of nearby communities and croplands. A 2020 study estimated that mangroves provide over $65 billion per year in global flood protection benefits (Menéndez *et al*, 2020).

This protective function is also evident in Odisha, India (Figure 14). During the devastating 1999 super-cyclone, Badola and Hussain (2005) compared three villages with different levels of mangrove protection. Bankual, shielded by an intact mangrove belt, not only suffered far less physical damage but also sustained significantly higher rice yields - averaging 1,479 kg ha^{-1}. In contrast, yields in Singdi, which lacked any protection, fell to 531 kg ha^{-1}, while in Bandhamal, protected only by an embankment, yields collapsed to 336 kg ha^{-1}. Beyond yield differences, households in the mangrove-protected village faced markedly lower costs of repair and reconstruction, reflecting reduced losses to houses, livestock, and crops. These findings demonstrate that mangroves act as a living shield: they buffer communities against immediate cyclone impacts while also preserving the agricultural productivity that underpins recovery. In short, mangrove belts transform extreme events from existential threats into manageable shocks, securing both livelihoods and rice production in highly vulnerable coastal regions.

Figure 14: Map showing the location of Odisha state, India (highlighted in red). Source: Wikimedia (licensed under CC BY 3.0 US).

In a similar study in Bangladesh's Sundarbans, Akber *et al*. (2018) found that villages sheltered by mangroves incurred cyclone-related monetary losses of around US $1,025 per household, roughly half the losses suffered in villages without mangrove protection. While a survey reported that 93% of surveyed households valued mangroves for their storm protection function, underscoring both their ecological and social importance in disaster risk reduction.

On a broader physical scale, modelling shows that intact mangrove belts can reduce storm surge height by 40–50 cm per kilometer of forest (Zhang *et al*, 2012), offering a natural form of coastal defense that no engineered structure can replicate at comparable cost. Together, these studies show that mangroves are not only ecological assets but also critical infrastructure for rice landscapes: they reduce cyclone damages, sustain yields, lower household recovery costs, and buffer storm surges. Preserving mangroves is therefore not just a conservation priority but an investment in the resilience, food security, and livelihoods of rice-growing communities.

7.2 Mangrove Accretion

Beyond storm protection, mangroves also play a vital role in sustaining the physical foundations of rice landscapes. In dynamic delta regions, where land subsidence and sea-level rise threaten to submerge paddy fields, mangroves act as natural sediment traps. Their dense root systems capture suspended material and bind organic matter, gradually building soil and elevating the land surface.

In sediment-rich systems like the Mekong, mangroves can build vertically at rates of around 5–10 mm per year (Woodroffe *et al.*, 2016). This process is vital in a region where intensive groundwater pumping and land-use change are driving subsidence of about 16 mm per year on average, with local hotspots sinking as fast as 40 mm per year. Figure 15 illustrates this subsidence dynamic in the Mekong Delta, mapping the spatial distribution of aquifer drawdown, compaction-based land subsidence, and satellite (InSAR) measurements between 2006 and 2010. Contour lines show the intensity of aquifer drawdown (purple/blue, cm/yr) and compaction-based subsidence (green/yellow, cm/yr), while the InSAR map (bottom) depicts satellite-measured land sinking (cm/yr).

Together, the panels highlight hotspots where groundwater pumping accelerates land subsidence. These patterns show how groundwater extraction is accelerating land sinking at a pace far exceeding natural vertical soil formation. While mangrove accretion contributes some vertical build-up, the rates of groundwater-driven subsidence mapped by Erban et al. (2014) are far higher, so even intact mangrove belts can only marginally slow net land sinking and cannot realistically

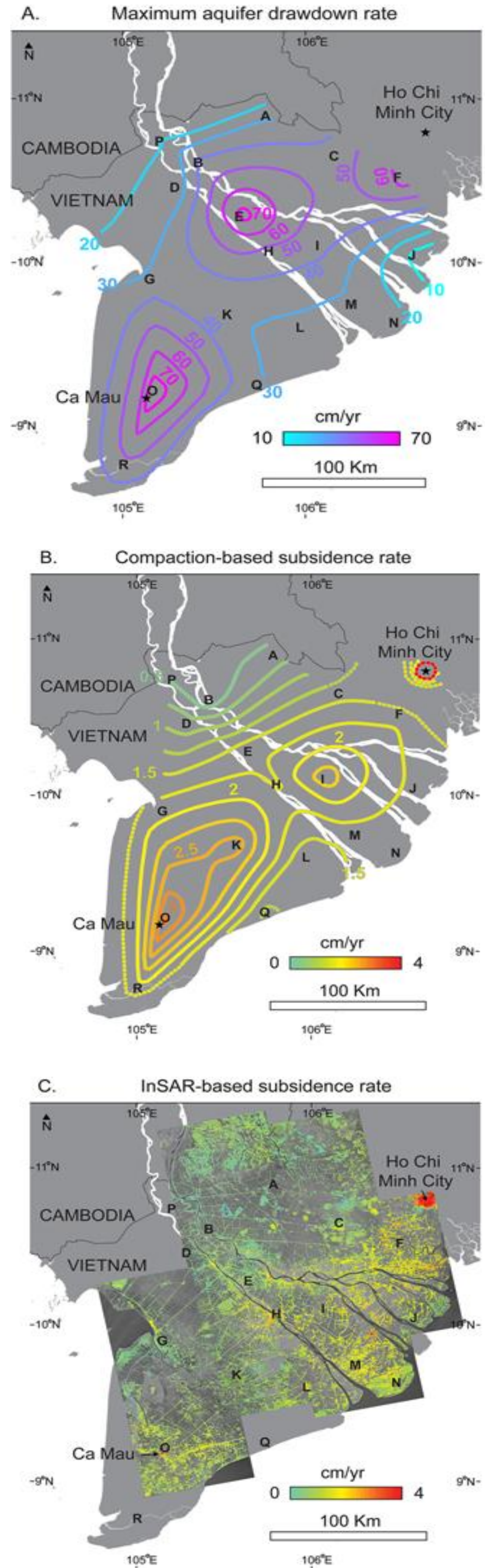

Figure 15: Groundwater extraction and subsidence in the Mekong Delta. Source: Erban et al. (2014), licensed under CC BY 3.0.

counteract widespread land subsidence. These subsidence hotspots are also part of a wider set of pressures on the Mekong system. Upstream forest loss, hydropower dams that trap sediment and dampen flood peaks, expanding irrigation schemes and intensive sand extraction are all altering how water and sediment move through the basin.

For rice landscapes in the Mekong Delta and other coastal plains, this means that mangroves and coastal wetlands provide more than short-term protection: they underpin long-term resilience by trapping sediment, slowing relative sea-level rise, reducing salinity intrusion, and preserving the shallow, fertile land that rice cultivation depends on. Where these natural sediment-trapping processes are disrupted, subsidence and sea-level rise together can rapidly lower the relative land surface, threatening to submerge large areas of productive rice land within decades.

7.3 Carbon and Greenhouse Gas Balance

Mangroves are among the most carbon-rich ecosystems in the world, storing on average 361 Mg C ha^{-1} in the top meter of soil - nearly three times the carbon density of croplands (127 Mg C ha^{-1}) and more than double that of many tropical forests (151 Mg C ha^{-1}) (J. Sanderman, 2018). Globally, this amounts to 6.4 Pg C in the top meter and 12.6 Pg C to two meters, with the densest stocks concentrated in South and Southeast Asia - regions that also host some of the world's most intensive rice production (Figure 16). The global map highlights soil organic Carbon (SOC) density hotspots, with local examples shown for (A) India–Bangladesh, (B) Panama, (C) Papua, Indonesia, (D) Australia, (E) Madagascar, and (F) Guinea–Bissau. Color shading represents SOC stocks per hectare, from lower values (yellow, ~90 metric tons SOC/ha) to very high values (dark blue, >800 metric tons SOC/ha). Together, the panels illustrate the geographic variability of carbon storage across mangrove ecosystems.

The consequences of their loss are substantial. Between 2000 and 2015, global mangrove conversion committed soils to releasing 2.0–8.1 Tg C yr^{-1}, with Indonesia, Malaysia, and Myanmar alone accounting for 77% of this loss. Conversion pathways matter: shrimp ponds and rice fields cause rapid and near-complete loss of soil carbon in the upper meter, undermining centuries of carbon accumulation (Sanderman *et al.*, 2018). Beyond stored carbon, the shift from mangroves to rice systems also alters greenhouse gas fluxes. Long-term monitoring indicates that around 40% of tropical mangroves have been lost over the past 80 years, including about 10.5% of those in the Sundarbans, due to sea-level rise, extreme weather, and human activity (Padhy *et al.*, 2021). Field measurements reveal that rice paddies emit mean CH_4 fluxes of 2665 μg m^{-2} h^{-1}, over 16 times higher than degraded mangroves (159 μg m^{-2} h^{-1}), while N_2O fluxes are also slightly higher in rice (72 vs. 69 μg m^{-2} h^{-1}) (Padhy *et al.*, 2023). These comparisons highlight that replacing mangroves with rice fields not only strips away long-term carbon stocks but also drives stronger ongoing greenhouse-gas emissions.

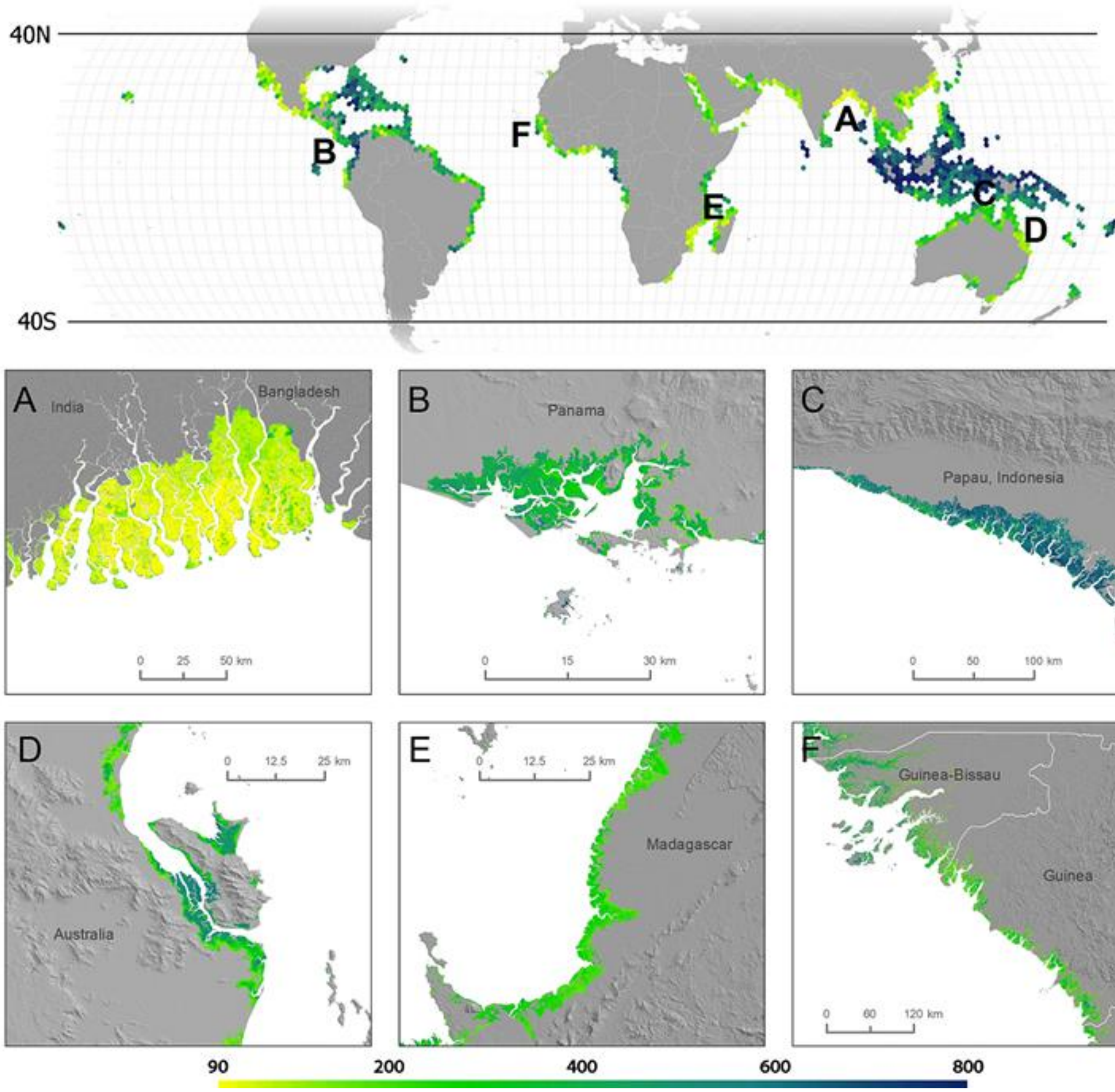

Figure 16: Global distribution of mangrove soil carbon stocks (0–1 m depth). Source: Sanderman et al. (2018), licensed under CC BY 4.0.

7.4 Conversion and pressures

Despite their ecological and protective value, mangroves have faced rapid decline. In the last 50 years, 30–50% of global mangrove area has been lost, with ongoing annual losses of around 2%. The main drivers include deforestation for aquaculture ponds, rice expansion, and coastal development. This scale of destruction is disproportionate to their extent: although mangroves account for just 0.7% of tropical forest area, their degradation may contribute up to 10% of global emissions from deforestation (Conservation International, 2019). This loss has been particularly acute in South and Southeast Asia, where high population densities and export-oriented aquaculture have reshaped entire delta landscapes.

In some cases, farmers have adapted to rising salinity by integrating shrimp and rice within former mangrove landscapes. In coastal Bangladesh, for example, smallholders cultivate rice–shrimp mosaics that can deliver rice yields of around 2.1 t ha^{-1} while providing additional income from aquaculture (Ahmed *et al*., 2023). Monsoon flooding helps flush salts each year, so these systems can function as a pragmatic response where salinity intrusion is already unavoidable. However, when management becomes more shrimp-dominated and intensive, salinity and soil degradation can persist, production becomes highly vulnerable to disease outbreaks, and long-term fertility declines, ultimately risking both rice productivity and ecosystem resilience.

These pressures highlight a critical trade-off: replacing mangroves with simplified production systems may provide immediate economic gains, but it undermines long-term climate stability, ecosystem services, and the sustainability of rice-based livelihoods.

7.5 Takeaway: Mangroves and the Nexus

Mangroves provide multiple ecosystem services that directly sustain rice-growing communities: they buffer storms and reduce cyclone damage, trap sediments and build soils that keep deltas above sea level, and act as globally significant carbon sinks with far lower greenhouse gas fluxes than rice or shrimp. In some coastal zones, seasonal rice–shrimp rotations have emerged as an adaptation to salinity intrusion, but when mangrove belts are cleared and replaced by simplified, shrimp-dominated monocultures these benefits are lost, and systems remain highly vulnerable to disease shocks. The trade-off is clear: short-term food or income gains from mangrove clearance come at the expense of long-term resilience and sustainability. Within the nature–climate–food nexus, protecting mangroves is therefore not only a conservation priority but also a strategy for climate mitigation (SDG 13), food security (SDG 2), and life on land and below water (SDG 15 & SDG 14) in vulnerable delta regions.

8. Water Systems and Rice Landscapes

Rice cultivation is concentrated within river basins, deltas and floodplains, making it tightly coupled to the behavior of the wider water system – rivers, lakes, wetlands, aquifers and their upstream catchments. Wetlands and floodplains act as hydrological buffers and nutrient recyclers, while river basins and watersheds regulate the timing and magnitude of flows, enhance groundwater recharge and moderate sediment transport. In combination, these water systems form the ecological and hydrological foundation that sustains the stability and resilience of rice production; when they are degraded or heavily engineered, the costs reappear as higher flood and drought risk, greater reliance on hard infrastructure and loss of biodiversity.

8.1 Ecosystem Functions of Wetlands and Floodplains

Wetlands not only underpin the hydrology of rice systems but also deliver multiple ecosystem services that directly support cultivation. By absorbing and storing floodwaters, they mitigate disaster risk and smooth out hydrological extremes. The Tonlé Sap floodplain in Cambodia, for instance, has historically redistributed seasonal Mekong floodwaters through a unique "reverse flow," in which the Tonlé Sap River switches direction during the monsoon, carrying water from the Mekong back into the lake. However, reductions in this reverse flow of around 56% since the 1960s–70s have shortened flood duration in the Tonle Sap by up to 40 days, diminishing water and nutrient delivery to rice

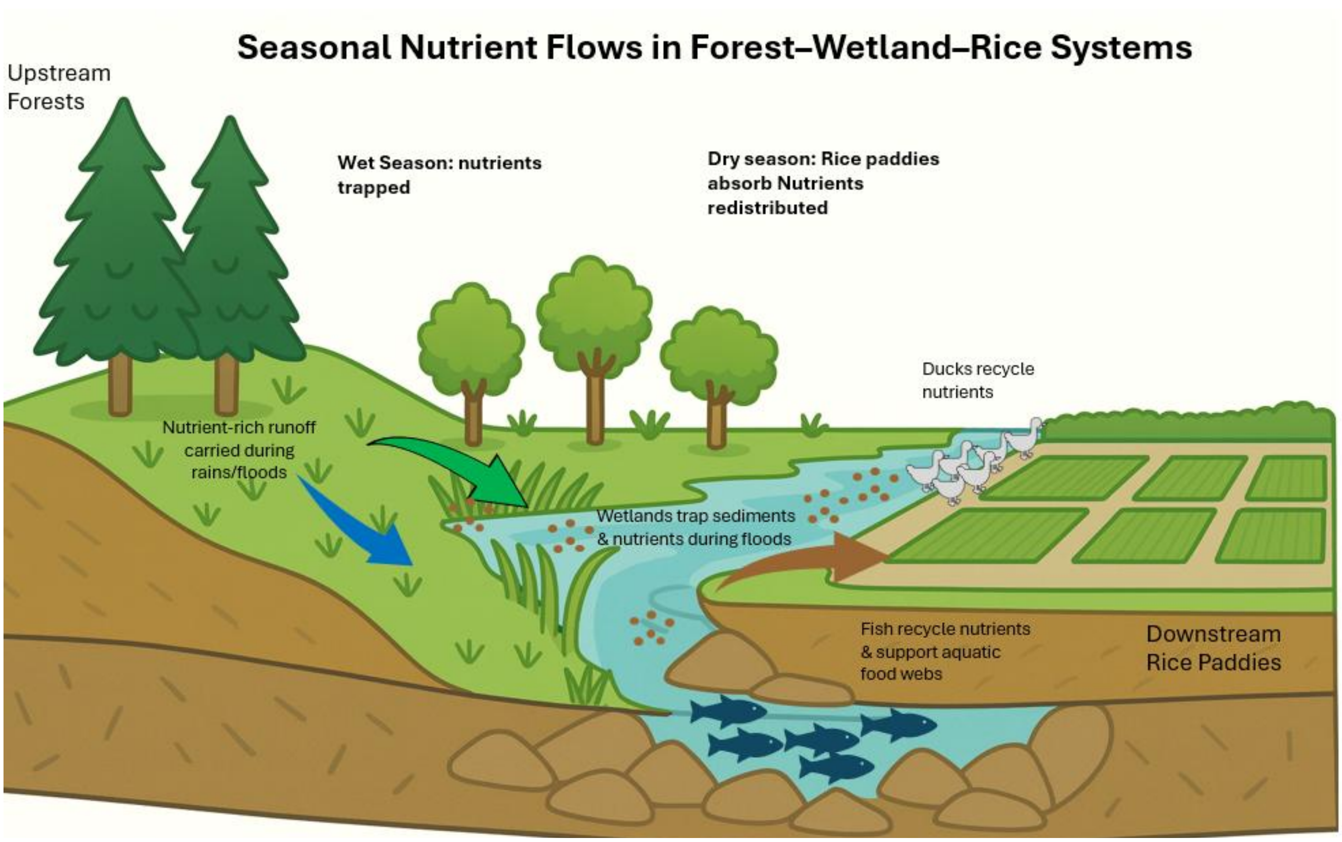

Figure 17: Interactions of nutrient cycling across forest–wetland–rice systems

fields downstream (Chua et al., 2022). Recent work in Cambodia's Mekong floodplains shows how this attenuated flood pulse, combined with heat, water stress and pest risks, is already reshaping agroecological zones and cropping calendars, and argues for "water-led" climate adaptation that targets irrigation investments to the most suitable rice areas while promoting diversification in more vulnerable zones (Harris et al., 2024).

Wetlands also trap sediments and recycle nutrients, sustaining soil fertility and reducing dependence on external inputs. In the Vietnamese Mekong Delta, seasonal inundation once carried nutrient-rich silt to paddy fields, but widespread construction of high dikes has disrupted these connections, cutting off natural fertilization and increasing reliance on chemical fertilizers. Further upstream in Cambodia, floodplains are still regularly inundated, yet the flood pulse is shrinking in duration and magnitude as dams trap sediment and attenuate peak flows, and sand mining in the Mekong sinks the river channel, gradually reducing natural nutrient inputs to rice fields.

Finally, wetlands provide habitats that sustain aquatic biodiversity, which form part of the ecological foundation of rice landscapes. As highlighted earlier, rice fields and adjacent wetlands can support high densities of waterbirds. For example, Paulino *et al*. (2024) documented 52 waterbird species using paddies, nearly as many as adjacent lakes, while Lourenço & Piersma (2009) showed that flooded rice paddies hosted bird densities closely matching natural estuarine wetlands. These findings demonstrate how wetlands and rice agroecosystems are tightly coupled in sustaining biodiversity, with implications for both ecological health and rice-based livelihoods.

The benefits of wetlands cannot be sustained without the integrity of their upstream watersheds, which regulate the timing, quality, and quantity of water reaching floodplains and rice paddies. Forests and upland soils function as hydrological sponges, capturing rainfall and releasing it slowly. This process sustains dry season flows and buffers extreme events. When disrupted by deforestation, however, runoff accelerates, infiltration declines, and the risks of both downstream flooding and prolonged drought increase.

8.2 Watersheds, Groundwater and Irrigation Trade-offs

Rice landscape management within watersheds can strongly influence groundwater recharge and downstream water availability. In the Inner Niger Delta, for example, large-scale upstream irrigation withdrawals for rice have reduced the extent of seasonal inundation by 6–10%, undermining groundwater recharge and destabilizing the coupled rice–floodplain production systems that rely on predictable flood pulses (Bonkoungou *et al*., 2024).

Similar concerns are emerging in the Indo-Gangetic Plains, a global groundwater-depletion hotspot where intensive pumping for monsoon rice has driven average water-table declines of ~0.4 m yr^{-1} (Deb et al., 2025). Farm-level flow-metering in north-western India shows that mechanized dry direct-seeded rice (DSR) can raise yields and irrigation water productivity compared with puddled transplanted rice, but that irrigation applications remain 1.6–2 times higher than in research trials and income pressures often push farmers from double to triple cropping, eroding potential water savings (Deb et al., 2025). Furthermore, agro-hydrological work in Eastern India maps “sustainable groundwater irrigation investment zones”, indicating that relatively modest increases in irrigation in groundwater-secure, high-response areas (for example in northern Bihar) could deliver large yield gains, whereas current investments often favor already water-stressed zones, locking farming systems deeper into unsustainable pumping pathways (Urfels et al., 2024).

Equally important is the role of healthy watersheds in controlling erosion and sedimentation. Intact forested catchments limit soil loss and safeguard reservoirs and irrigation canals, while degraded watersheds accelerate siltation, reduce storage capacity and raise maintenance costs. In rice-dependent deltas and basins, where irrigation infrastructure underpins millions of hectares of cultivation, such losses directly translate into reduced system resilience.

However, these regulating functions are increasingly compromised by human pressures. In the Mekong Delta, the spread of high-dike systems has severed connections between rivers and fields, cutting off natural sediment and nutrient inflows. In An Giang province, surveys of farmers report that fish diversity in high-dike floodplain areas has declined by 75–81% following their construction (Da *et al*., 2024). In upland catchments, deforestation accelerates erosion and sedimentation, further reducing the long-term reliability of irrigation systems. These drivers, compounded by climate variability, undermine the ecological foundations of rice production and highlight the urgency of maintaining landscape integrity.

Taken together, wetlands and watersheds form an integrated ecological infrastructure that connects nature, climate, and food systems. When intact, they stabilize hydrology, deliver nutrients, and sustain biodiversity, providing the foundations of resilient rice production. When degraded, these functions are lost, forcing greater reliance on artificial inputs and engineered water control, while heightening vulnerability to floods, droughts, and other climate shocks. Thus, safeguarding wetlands, river basins and watersheds goes beyond biodiversity conservation, serving as a nature-based adaptation strategy that supports food security and strengthens climate resilience.

9. Policy Pathways and Adaptation

Protecting rice resilience requires aligning forest and river-basin science with governance, finance and farmers' realities. Forests regulate rainfall and moisture recycling, while river basins, wetlands and watersheds buffer and distribute this water, recharge groundwater and transport nutrients. Yet institutions and investments remain fragmented: agricultural policy often prioritizes short-term yield gains without attention to ecological processes, while environmental policy focuses on conservation without engaging farmers as partners in landscape management.

To put this into practice, we first need clear, spatially explicit diagnostics: maps that show which forests, wetlands and stretches of river matter most for particular rice systems, and how they are being used or degraded.

On this basis, policy and investment can support concrete solution sets: improved water and input management in rice areas, nature-based options such as agroforestry, rice–fish and mangrove protection, and value-chain upgrading that rewards more sustainable practices. Equally important is understanding the social and economic constraints that limit farmers' ability to adopt these options and addressing the local drivers of land-use change or inaction.

Ultimately, bridging this divide requires a unified agenda that embeds forests, wetlands, and river basins into agricultural, trade, and climate policy, treating them not only as externalities but as core infrastructure for resilient, sustainable rice-based food systems.

9.1 Knowledge and extension

Farmers already manage ecosystems through practices such as rice–fish systems or flood-based farming, which can be validated and scaled through extension services. Modern tools can amplify this knowledge: for example, user-friendly decision-support systems could show how leaving riparian tree strips reduce flood risk or enhances pollinator services, while participatory monitoring can track local water and biodiversity benefits. In many countries, however, basic environmental information on flows, groundwater, water quality and habitat condition is still sparse. Low-cost digital systems, from satellite-based land and water monitoring to simple sensors and phone-based reporting, combined with participatory monitoring can help build the data needed to manage rice landscapes more effectively. Building on this, integrated agroecological, hydrological and economic models with sufficient spatial resolution at national and regional scales are essential to identify where particular measures will deliver the greatest benefits.

At the policy level, scenario models that quantify trade-offs and co-benefits, such as, demonstrating how a modest investment in upstream reforestation translates into avoided flood damages and stable rice yields, can build economic arguments for ecosystem-based management. Embedding these approaches into cross-sector platforms ensures agricultural, water, and environmental agencies act in unison, reinforcing the principle that rice security is inseparable from ecosystem security.

9.2 Integrated Governance

A shift towards landscape-scale planning is essential, requiring integration across agriculture, forestry, and water management. Because many major rice basins and moisture-transport pathways cross national borders, this shift also has a transboundary dimension: diplomatic services, basin organizations and regional research networks need to work with line ministries to manage forests, water and rice systems at the scale of shared river basins. National rice development plans could incorporate explicit targets for retaining forest cover in critical basins that sustain irrigation flows, while zoning laws can secure wetland buffers and restrict conversion of floodplains that provide natural flood protection. Agencies that traditionally operate in silos - from agricultural extension to forest departments and irrigation authorities - should collaborate through joint programs. Landscape-scale initiatives for climate-resilient rice systems could play an enabling role by combining measures such as upland reforestation, agroforestry, integrated pest management in rice fields, and wetland restoration, alongside monitoring to track impacts on yields, water security, and biodiversity. There are already encouraging policy shifts in Asia. ASEAN's *Regional Guidelines for Sustainable Agriculture* already reflect this shift, emphasizing cross-sector collaboration and sustainable water and land-use management (Kozono *et al*., 2023). Furthermore, China's Ecological Conservation Redline (ECRL) is one of the world's most ambitious land-use frameworks, setting minimum areas for strict ecological protection to safeguard biodiversity and ecosystem services (Choi *et al*., 2021). The policy reduces forest loss, strengthens regulating services, and supports Sustainable Development Goals (Wang *et al*., 2024).

9.3 Economic Incentive and PES

Aligning farmer and community incentives with ecosystem stewardship is crucial for sustaining rice landscapes. Payments for ecosystem services (PES) can reward upstream forest and wetland conservation that stabilizes rainfall, reduces sedimentation, and maintains fisheries. These functions are often undervalued in markets. For example, in Japan's Kumamoto Prefecture, farmers are compensated for practices such as paddy flooding that recharge aquifers and secure municipal drinking water supplies (Shivakoti *et al*., 2018). In South America, watershed funds like *FONAG* in Quito, Ecuador, channel contributions from water users, municipal utilities, and stakeholders into upstream conservation and farmer training, directly linking urban water security with rural watershed management (Kauffman & Echavarría, 2012; Goldman *et al*., 2010).

Emerging climate finance and green investment approaches offer additional opportunities. Green bonds and carbon markets can recognize "forest-for-rain" functions, rewarding communities that conserve forests sustaining atmospheric rivers and rainfall for downstream rice systems. For example, Indonesia issued the world's first *sovereign green sukuk bond* in 2018 to fund sustainable land use and climate projects, demonstrating how such initiatives can channel resources toward ecological infrastructure. Similarly, payments linked to blue carbon could incentivize the protection of mangroves, which buffer coastlines and hold some of the densest soil carbon stocks globally. The *Mikoko Pamoja* project in Kenya already does this, selling verified carbon credits from mangrove conservation and reinvesting revenues into community development. Together, these mechanisms shift conservation from a cost to a viable livelihood strategy, embedding ecosystem protection within the economics of rice production and food security.

9.4 Certification Schemes

Certification offers a market-based pathway to reward sustainable rice production. The Sustainable Rice Platform (SRP), co-led by UNEP and IRRI, has developed a global standard with performance indicators addressing water efficiency, greenhouse gas emissions, and biodiversity protection (SRP, 2023). Early adoption in Thailand, Vietnam, and India shows that SRP-verified rice can reduce inputs, improve farmer incomes, and secure access to premium export markets. Expanding the criteria to include watershed and wetland protection would strengthen incentives for landscape stewardship, while linking certified rice to climate-smart procurement and carbon markets could mobilize additional investment.

9.5 Sustainable Consumption

Demand-side measures are essential to reinforce ecological production practices. A powerful lever is public procurement: state food distribution systems, school feeding programs, and subsidy schemes in major rice economies buy vast volumes and could embed sustainability criteria to reward landscape stewardship. For example, India's Public Distribution System (PDS) serve hundreds of millions of people, meaning even modest shifts toward ecosystem-linked procurement would reshape demand.

Furthermore, as global buyers increasingly prioritize traceability and low-carbon supply chains, rice produced under sustainability standards can access premium markets and influence broader adoption. Importantly, demand is also emerging within Asia's growing urban middle classes, in countries like Thailand, Vietnam, and India, domestic retailers and e-commerce platforms are beginning to market "sustainable rice" as a premium product. By linking consumer recognition to the ecological foundations of rice, forests, wetlands, and watersheds, sustainable consumption can create bottom-up pressure that reinforces policy reforms and producer incentives.

10. Conclusion

This report demonstrates the deep interdependence between rice production and the ecosystems that sustain it. Forests, rivers, wetlands, mangroves, and biodiversity are not passive backdrops but active systems that regulate water, carbon, and nutrient cycles. Atmospheric rivers seeded by forests and croplands deliver the rainfall that underpins monsoon-dependent rice basins; river basins and wetlands buffer floods, recharge aquifers, and recycle nutrients; mangroves shield coastal rice landscapes from storms and sea-level rise; and biodiversity (visible and invisible) anchors both productivity and resilience. Together, these ecosystems operate as living infrastructure and sustaining ecosystem integrity underpins the resilience of rice systems which are crucial for sustainably delivering stable food supplies under mounting climatic and demographic pressures.

At the same time, this review paper underscores the vulnerability of the ecological foundations of this nexus. Deforestation, wetland drainage, mangrove conversion, and biodiversity loss disrupt the very processes that secure water, fertility, and climate regulation. As rice systems intensify to meet rising demand, they risk eroding the ecological foundations of their own productivity, generating disservices such as greenhouse gas emissions, nutrient ru noff, and biodiversity collapse. The trade-off is clear: short-term yield gains achieved at the expense of natural infrastructure undermine long-term resilience and food security.

The pathways forward are equally clear. Embedding ecological knowledge into agricultural policy, finance, and consumption can transform these trade-offs into synergies. Incentives for forest and watershed conservation, certification schemes that reward ecological rice production, and procurement systems that prioritize sustainability, can align farmer livelihoods with ecosystem stewardship. Scaling agroforestry, rice–aquatic integration systems, and biodiversity-friendly management practices, can restore local resilience. While climate finance and nature-based adaptation strategies, can leverage global resources to safeguard ecosystems that secure regional food systems, they also need to be guided by a clear sense of where rice remains an adaptive land use and where alternative crops or land uses could provide better water, carbon and risk-regulation services without undermining food security. By recentering nature as the operating system of rice agriculture, this review highlights both the urgency and the opportunity: the resilience of rice landscapes, providing the staple food for half the world's population, depends on nourishing and strengthening the ecosystems that rice systems are part of. Securing the nexus between nature, climate, and food is therefore not only a matter of conservation, but a strategic imperative for global food security, climate stability, and sustainable development.

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