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RESEARCH REPORT

The Science of Agriculture-Driven Nature Loss (Part 1): Mapping Drivers and Impact of Agricultural Water Management

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About Multifunctional Landscapes

Multifunctional Landscapes is a CGIAR Science Program that aims to enhance the resilience, productivity, and sustainability of agricultural landscapes by integrating diverse land uses, ecosystem services, and livelihood strategies. The initiative supports evidence-based policies and innovations that balance food production with climate adaptation, biodiversity conservation, and social inclusion. By working with local communities, governments, and partners, it promotes landscape-level approaches to managing natural resources for long-term ecological and economic benefits. To learn more about the CGIAR Research Portfolio, please visit www.cgiar.org/cgiar-research-portfolio-2025-2030/

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF BOXES

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1. INTRODUCTION

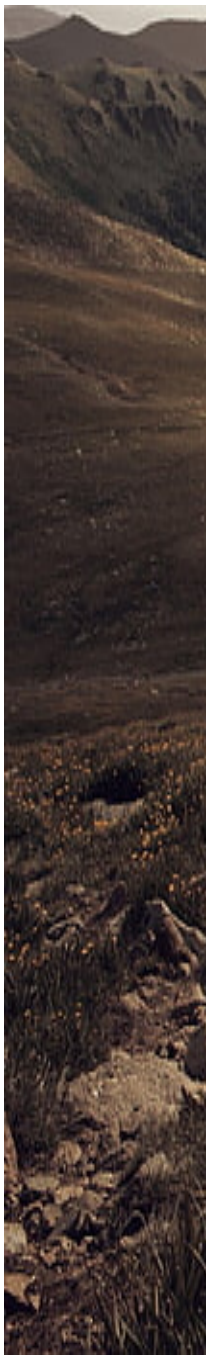
The accelerating loss of biodiversity and ecosystem degradation represent one of the most profound global challenges of the twenty-first century. Scientific consensus shows that nature is declining at unprecedented rates in human history, with approximately 1 million animal and plant species currently threatened with extinction (IPBES, 2019). The decline undermines the ecological foundations of ecosystem services that sustain agriculture, including soil fertility, water regulation, pollination, and climate regulation, jeopardizing long-term food security and ecosystem resilience. Furthermore, biodiversity loss is not solely an ecological issue; it also undermines the biophysical basis of human well-being, economic stability, food security, and climate resilience, putting both natural systems and societies at risk (Scott et al., 2024; Almeida et al., 2025).

Agricultural systems lie at the center of this crisis. Agricultural expansion, intensification, and associated land-use change have been identified as dominant drivers of terrestrial and freshwater biodiversity loss. In a recent global empirical synthesis, Jaureguiberry et al. (2022) demonstrate that land/sea use change is the most significant direct driver of recent anthropogenic biodiversity loss, followed by direct exploitation of natural resources and pollution; climate change and invasive alien species had comparatively smaller relative impacts. Intensification further compounds these pressures through increased agrochemical inputs, soil degradation, nutrient loading, over-abstraction of water resources, and homogenization of landscapes. Together, these processes diminish key ecosystem services (ESs) at scales and threaten the long-term sustainability of agricultural production itself (Scott et al., 2024). The implications extend beyond ecological systems. Recent macroeconomic analysis has demonstrated that nature degradation directly affects total factor productivity, exacerbates supply-chain vulnerabilities, amplifies financial risk, and can reduce global GDP by up to 2.3%, rising to as much as 10% in low-income economies dependent on natural capital (Almeida et al., 2025). Furthermore, more than 70% of emerging infectious diseases have been linked to ecosystem disruption, indicating that unchecked nature loss heightens systemic risks across environmental, economic, and health domains (Espinosa et al., 2020). In recognition of the global urgency, the Kunming–Montreal Global Biodiversity Framework has set an ambition to halt and reverse nature loss by 2030 through transformative change in key sectors, including agriculture (CBD, 2022). Central to this ambition is the reform of agricultural practices, planning systems, and governance structures to align production landscapes with biodiversity conservation and sustainable ecosystem management. Several scholars emphasize that addressing agricultural drivers of biodiversity loss necessitates systemic interventions, including multifunctional land-use strategies, biodiversity-inclusive spatial planning, and mechanisms that integrate ecological values into decision-making (Scott et al., 2024; Jaureguiberry et al., 2022).

Given this context, there is an urgent need for cross-scale synthesis of scientific evidence on the links between agricultural practices and biodiversity outcomes. The report contributes to this endeavor by systematically mapping and synthesizing mechanisms across soil, water, land-use, pollution, and ecological dimensions through which agriculture impacts biodiversity and ecosystem functioning. Specifically, the drivers and impacts of agriculture-driven nature loss are mapped via the triple lens of mismanagement of natural resources, biophysical changes, and climate change. Focus is given to environmental stressors that may induce physical, chemical, and biological changes, as well as to their primary impacts on biodiversity and ecosystem services. The work provides a foundation for identifying priority intervention points to support the development of nature-positive agricultural transitions. Such clarity is necessary not only for advancing scientific knowledge but also for informing policy processes, national biodiversity strategies, and global commitments to sustainable and resilient food systems.

2. METHODOLOGY

A scoping literature review was conducted to identify, assess, and synthesize interrelated ideas and current understanding of how agriculture broadly affects biodiversity and ecosystem services (BESs). We identified direct and indirect drivers, but primarily focused on the former, given that the study centers on advocating for sustainable practices. The drivers were prioritized and selected, provided they meet one of three criteria: agricultural practices i) have universal or widespread relevance, ii) severely impact BESs, and iii) have cumulative and interconnected impacts.



Universal or Widespread Relevance

This implies that the drivers have a global presence, occur simultaneously in multiple locations worldwide, and practices are widely used across one or more ecosystems. For instance, monoculture agriculture and agrochemicals are commonly used in various farming environments. These practices transcend boundaries, despite local/regional disparities and pose common challenges.

Severely Impacts Biodiversity and Ecosystem Services

These drivers can cause large-scale damage to ecological systems and the services they provide, though the severity of harm may vary across trophic levels or functional groups. Severity *refers* to the intensity of harm, such as significant habitat destruction, drastic declines in species populations, or major disruptions to ecological processes. Large-scale impact *refers* to the broad geographic extent of these effects, affecting vast areas or multiple ecosystems. For example, water pollution can severely compromise ecosystems' capacity to provide and regulate ecosystem services, including purification and water supply. It can cause immediate and long-term harm to many freshwater and marine species. Critical habitats such as coral reefs, seagrass beds, and mangroves that support wildlife and marine life can be affected. Vital ecological processes, including nutrient cycling, predator-prey relationships, and food webs, can be affected at various trophic levels.

Cumulative and Interconnected Impacts

The drivers are closely linked and have combined effects on ecosystems. They can accumulate across time and space and interact in ways that amplify their effects, resulting in severe and widespread consequences that individual factors alone cannot produce. Over time and across different regions, the combined effects can result in significant ecological degradation. For example, high levels of nutrient runoff from agriculture can exacerbate algal blooms, whereas changes in precipitation patterns can alter hydrologic flow and dilution, thereby affecting pollutant concentrations. This can amplify the release of toxic substances and the degradation of water quality, thereby increasing greenhouse gas emissions that accelerate climate change. When these stressors accumulate and interact, their combined effects on ecosystems can be profound, including pollution and climate change, altered species interactions, and changes in ecosystem services such as nutrient cycling. Warming water conditions can also increase the toxicity of certain pollutants, further stressing aquatic organisms and degrading ecosystems

Based on the information above, Figure 1 illustrates the framework developed to depict the relationships between agricultural practices and their impacts on BESs. A modified Driving Force-Pressure-State-Impact (DPSI)[1] framework was used to establish causal relationships between agricultural practices (drivers) and their impacts on BESs. While drivers are often described as underlying socioeconomic and cultural factors motivating human activities, in this study, drivers are defined as specific agricultural activities, such as over-irrigation and surface flooding, exerting environmental stressors (pressures) such as waterlogging conditions, etc. These drivers were mapped to one of three agricultural domains: water resource management, soil and land management, and waste and pollution management. Each driver/sub-driver was also mapped to at least one of these farming typologies: (1) farms on forest frontiers; (2) agrochemical-intensive monocultures; (3) intensive livestock systems and overgrazing; (4) water (over) extractive farming.

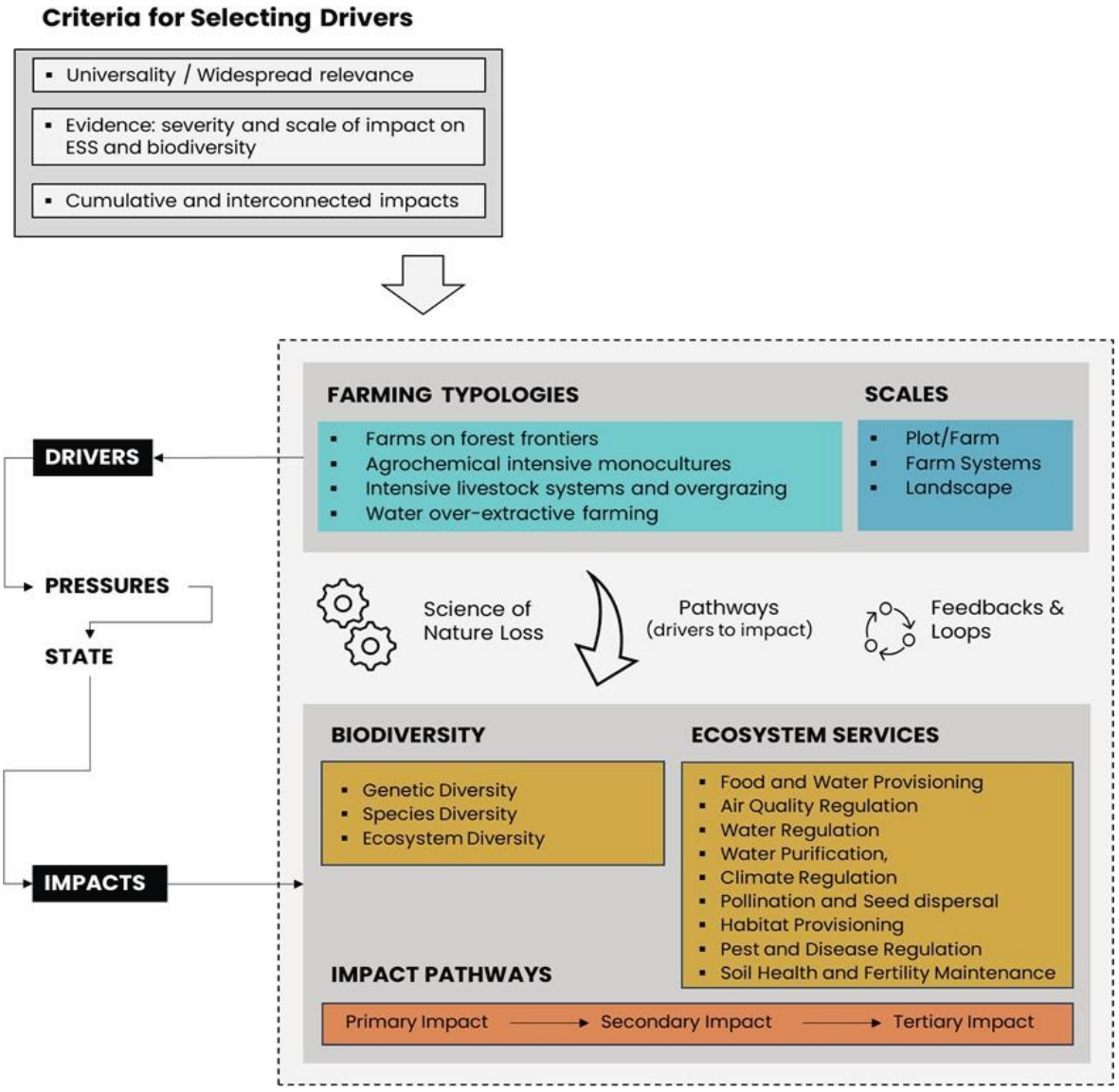


Figure 1 *− A guiding framework for mapping drivers and impacts of agriculture-driven nature loss.*

Source: Authors

[1]The standard DPSIR represents the Driving Forces, Pressures, State, Impact, and Response; the modified DPSI excludes the response element

Table 1: Agricultural drivers and sub-drivers of nature loss by management area and farm typologies. The table shows en (10) key agricultural practices as direct drivers of biodiversity loss and declining ecosystem services.

DRIVERS	SUB-DRIVERS	DESCRIPTION / CONTEXT	FARM TYPOLOGIES[2]
AGRICULTURAL WATER MANAGEMENT			
Irrigation water management	**1. Surface (flood) irrigation**	Traditional methods of irrigating agricultural fields by flooding with water; often linked with large (canal) irrigation.	1,4
	2. Poor scheduling of irrigation water	Leading to under-/over-irrigation due to insufficient or poorly applied irrigation methods.	1
	3. Poor irrigation water quality	Use of low-quality/marginal water, e.g., brackish, for irrigation/fertigation.	1,2
Over-exploitation of water resources	**4. Over-abstraction of surface and/or groundwater**	Over-abstraction of water for intensive agriculture or livestock production, where withdrawal exceeds recharge.	3,4
Watershed Management	**5. Wetland drainage and conversion**	Using natural or engineered modifiers to remove water actively; channeling water to lower water level areas; wetland conversion into agricultural land that leads to drainage and destruction of floodplains.	2,4
	6. Poor construction and management of reservoirs	Inadequate construction and distribution, e.g., canal operations for agriculture (illustration not provided)	1,3,4
AGRICULTURAL SOIL AND LAND MANAGEMENT			
Crop management practices	**7. Monocropping and mono-culture**	A practice of growing a single crop/species on a specified land, period after period.	2,4
	8. Poor crop selection	A practice of choosing crops that are not well-suited or sub-optimal for local conditions	2,4
Soil management practices	**9. Excessive tillage**	Soil preparation methods that degrade soil structure, including the use of heavy machinery	1,2
	10. Poor soil and water conservation management	Inadequate or absent of in-situ soil and water conservation measures that expose the soil to dryness and erosion.	1,2
Land use change & management practices	**11. Land use change**	Conversion of forests, grasslands, or wetlands into agricultural lands. (illustration not provided)	2,3,4
	12. Shifting cultivation	Clearing forests for temporary crop cultivation and leaving some time to recuperate (illustration not provided)	1,2
Livestock farming management practices	**13. Poor livestock farming**	Practices involving overgrazing, removal of vegetation cover, and stocking density that lead to soil compaction	1,3
AGRICULTURAL POLLUTION MANAGEMENT			
Excessive herbicide and pesticide use	**14. Use of pesticides**	Untargeted application of chemical compounds to control unwanted plants/weeds	2
		Untargeted application of chemical compounds to control pests (including fungicides)	2
Excessive use of nutrients	**15. Fertilizer use**	Application of synthetic and/or organic fertilizer to supplement nutrients on farms	4
Poor agricultural waste management	**16. Poor crop residue and livestock waste management**	Improper handling and use of leftover crop residues and livestock waste in agriculture (illustration not provided)	4

[2]Farm typologies include: 1. farms on forest frontiers; 2. agrochemical-intensive monocultures; 3. intensive livestock systems and overgrazing; 4. water (over) extractive farming

The impact of various drivers on BESs is examined through the lens of pressure-state interactions. This study has adopted the definition of biodiversity from the 2019 IPBES report, which describes biodiversity as "the variability among living organisms from all sources, including terrestrial, marine, and other aquatic ecosystems, as well as the ecological complexes of which they are a part." This definition encompasses differences in genetic, phenotypic, phylogenetic, and functional characteristics, as well as temporal and spatial changes in abundance and distribution across species, ecological communities, and ecosystems. We have also adopted the typology of ecosystem services from the "The Economics of Ecosystems and Biodiversity (TEEB)" assessment framework, which categorizes ecosystem services into provisioning, regulating, habitat, and cultural services[3], in conjunction with the IPBES Assessment of Nature's Contributions to People (NCP). The study prioritized biodiversity-related ecosystem services, particularly those that regulate ecosystem processes and underpin ecosystem functioning. This includes air quality regulation, water regulation, water purification, climate regulation, pollination and seed dispersal, habitat provisioning, pest and disease regulation, and soil health and fertility maintenance. Impacts are assessed from the perspective of a decline in, or loss of, BESs. When possible, we discussed implications in terms of severity (short-term/long-term) and scale (plot/farm, farm systems, landscape) on various ecosystems and trophic levels. We also considered multiple connections among ecosystems; however, each driver is discussed separately, although they are extensively linked and have interconnected impacts. This study has not considered positive impacts and feedback, and has considered secondary and tertiary effects only to a limited extent. We also did not discuss conservation actions, policy measures, sustainable management practices, or solutions for protecting and restoring natural systems, as presented in related CGIAR reports.

Climate change is highlighted in two ways: first, as a driver of various environmental challenges, and second, as an outcome of agricultural management practices. This dual perspective underscores the far-reaching implications of climate change and emphasizes the critical importance of implementing effective and practical solutions to mitigate its effects. Climate impacts on ecosystems may be direct or indirect, but ultimately they exacerbate threats and interact with other stressors, including temperature changes, flow alterations, habitat fragmentation, and pathogen loads. While some natural disturbances associated with climate change may have transient positive effects on biodiversity and ecosystems, we have focused on their adverse impacts.

[3]Typologies of ecosystem services in "The Economics of Ecosystems and Biodiversity (TEEB)" assessment, categorized into provisioning, regulating, habitat, and cultural services and compared to the IPBES assessment of nature's contribution to people, are listed in (Supplementary Information I Table 1).

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3. AGRICULTURAL WATER MANAGEMENT AS A DRIVER AND IMPACT ON BIODIVERSITY AND ECOSYSTEM SERVICES

Water is an essential resource for agriculture. The use of freshwater for irrigation has greatly improved food production, even under increasing environmental uncertainty (Molden, 2007). Water also plays a crucial role in supporting ecosystems by enabling services such as soil fertility, nutrient cycling, and hydrological regulation, functions that directly sustain agricultural productivity (FAO, 2022). Although water is vital for both ecosystems and farming, its use in agriculture often involves important trade-offs (Pratap et al., 2023). When managed well, agricultural water supports food production, stabilizes yields, and sustains the landscapes on which communities depend. But when it is poorly managed, agriculture becomes a major driver of biodiversity loss and ecosystem degradation.

This risk is intensified by the sheer scale of water use in agriculture. As the world's largest water user, taking up nearly 72% of global freshwater withdrawals, agriculture puts significant pressure on rivers, groundwater, wetlands, and the biodiversity they support (Smith et al., 2024; Jing et al., 2025). Because of this immense footprint, the ways in which water is captured, stored, diverted, and distributed for farming play a decisive role in shaping the health of soils, freshwater ecosystems, and the species that depend on them.

Freshwater ecosystems are especially vulnerable. Although they cover less than 1% of the Earth's surface, they host nearly 10% of all known species, making them among the most biodiverse habitats on the planet. Yet irrigation and water abstraction often reduce river flows, shrink lakes, and lower groundwater levels. Well-known examples include the degradation of the Aral Sea, Lake Chad, and Lake Urmia, changes strongly linked to water diversion for irrigation (Smith et al., 2024). Such declines disrupt breeding grounds, feeding habitats, and migration routes for many aquatic species, thereby weakening the ecosystem services that support agriculture.

Poor water management can also indirectly reduce biodiversity. As Jing et al. (2025) show, irrigation runoff often carries fertilizers and pesticides into rivers and wetlands, causing eutrophication, algal blooms, and shifts toward a few pollution-tolerant species. In some rivers, a single zooplankton group now accounts for over 90% of all organisms, indicating that agricultural water pollution can simplify food webs and reduce ecosystem stability. As wetlands and rivers lose their natural diversity, services such as nutrient cycling, water purification, and habitat provision decline. Terrestrial biodiversity also responds to water management decisions. Irrigation canals and drainage structures can fragment landscapes, cutting off the movement of birds, insects, and small mammals. They may also act as pathways for invasive species, which spread easily through human-modified agricultural landscapes.

Thus, this section examines how different aspects of agricultural water management (AWM) contribute to these outcomes. It focuses on three key areas where poor practices create significant pressures on BESs: i) poor irrigation water management, ii) over-abstraction of water for crops and livestock, and iii) poor watershed management. Figure 2 illustrates how these water-related drivers interact and how their combined effects can undermine ecosystems. Links between soil and land management are explored in Part 2 of this report, whereas pollution- and waste-related interactions are discussed in Part 3.

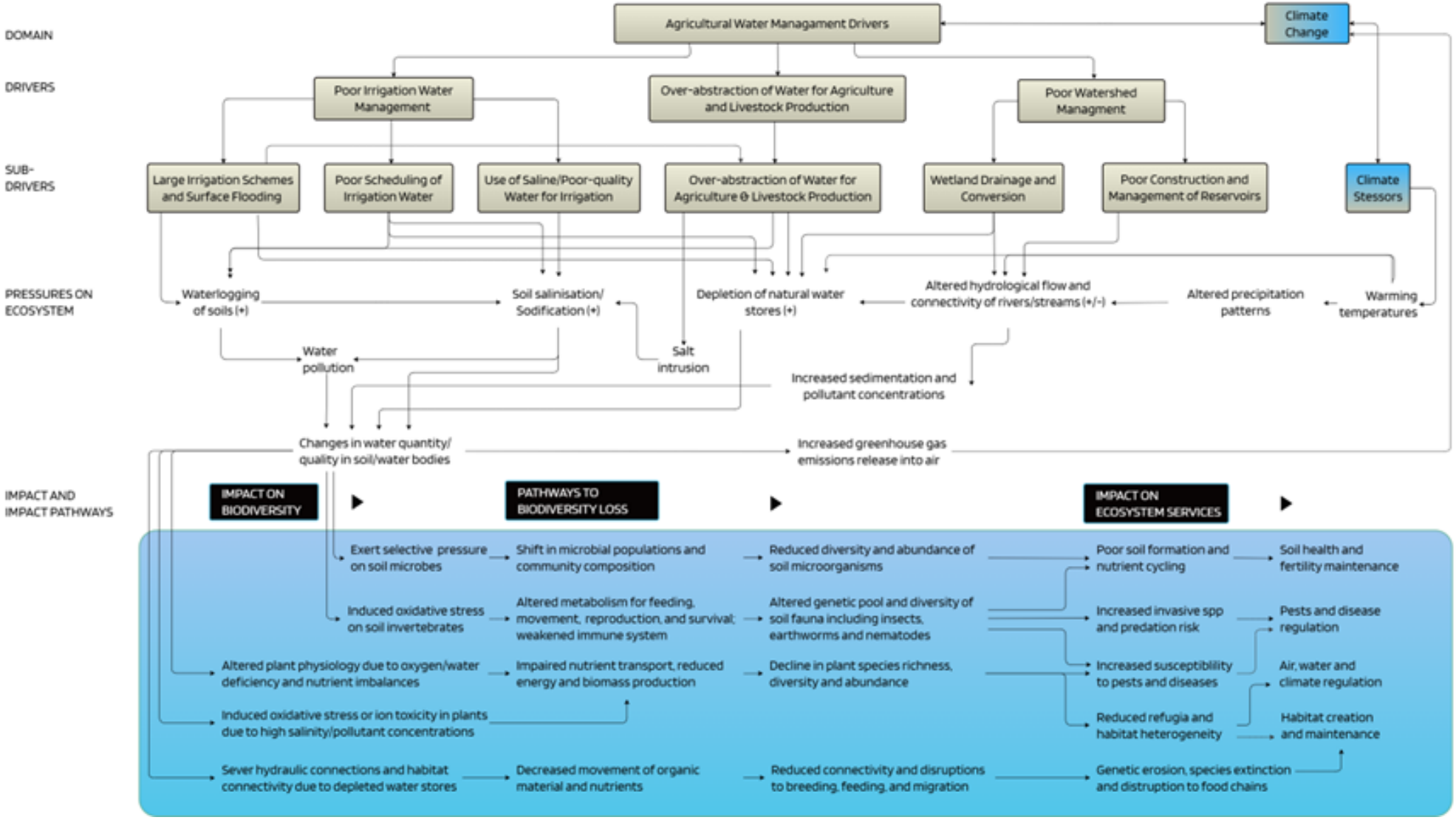

Figure 2 *– A high-level illustration of major agricultural water management drivers and their impacts on biodiversity and ecosystem services.*

Source: Tosin Somorin/IWMI

3.1. Poor Irrigation Water Management

The aim of irrigation management is to ensure that water is applied to crops at the appropriate time and in appropriate amounts. This is done to reduce wasteful water consumption and ensure that soils can effectively retain and supply water to crops at rates that match the soil's absorption capacity and erosion risks. However, in many agricultural settings, particularly in water-intensive agriculture and forest-frontier smallholders, irrigation water is poorly managed or distributed. Some of the widely reported poor irrigation water management practices include surface flooding, poor irrigation water scheduling, and using poor-quality water for irrigation (Chauhan & Ram, 2023; Chaube et al., 2023; Dangar et al., 2021; Manasi et al., 2019; Abdullaev et al., 2009; Bhattarai et al., 2021). The next subsections describe how these practices adversely impact BESs.

3.1.1. Poor Performance of Large Irrigation Systems and Flood Irrigation Practices

Large-scale irrigation schemes are crucial in regions where natural water availability is insufficient for agriculture. In India, Bangladesh, Pakistan, and many other Asian countries, such schemes have a long history, with canal irrigation as a primary method for supplying water to farmland. Pakistan's Indus Basin irrigation system is the world's largest contiguous scheme, with an area of 17 million ha (Sajid et al., 2024). The Ganges Basin in India, the Yellow River Basin in North China, and the Central Asian Republics similarly support some of the largest irrigation schemes in the world (Mukherji et al. 2009). Key examples include the Grand Anicut and the Vianagarum Canal systems, which have been used for centuries and continue to play a vital role in irrigation (Chauhan & Ram, 2023). While significant gains have been made in agricultural productivity, large-scale irrigation schemes have come with environmental costs. Qualitative analysis of large-scale schemes in India has shown that many canal irrigation systems are poorly designed, old, structurally damaged, and plagued by operational issues such as siltation, insufficient water conveyance, and high seepage losses (Chauhan & Ram, 2023). Many farmers employ flood irrigation in these contexts because of its simplicity and low cost. Freshwater withdrawal is unregulated, and government subsidies are available. Inadequate design and operational problems, as well as maintenance issues, have resulted in poor water distribution and control, low irrigation efficiency, and substantial water losses, leading to widespread surface flooding (Chauhan & Ram, 2023; Chaube et al., 2023). Commonly induced environmental changes include increased waterlogging, salinization, surface runoff, and aquifer depletion (Singh et al., 2012; Dinka & Ndambuki, 2013). The impacts of waterlogging and salinization are discussed in Boxes 1 and 2, respectively; however, the effects of water over-abstraction and their implications for storage and environmental flows are discussed in Section 3.3. The contributions to water pollution are discussed in Part 3 of this report.

Box 1: Waterlogging Impacts

Waterlogging occurs when soil becomes saturated, causing water levels to rise. In dry-irrigated fields, free water percolates, but waterlogging can arise from shallow groundwater and from large seepage losses due to uncontrolled drainage and unlined canal networks, resulting from poor water-holding capacity and soil drainage conditions (Singh et al., 2012; Dinka & Ndambuki, 2013; Manghwar et al., 2024). The most common cases of waterlogging are reported in the irrigated Indus Basin of Pakistan and India, where wheat, rice, cotton, and sugarcane are grown (Singh, 2015; 2016). These regions are characterized by high rainfall and dense irrigation systems. Countries such as Bangladesh, India, China, and Vietnam also often experience waterlogging, particularly in areas with poorly managed irrigation systems.

Waterlogging primarily affects soil ecosystems and plant physiological processes, both of which are inextricably linked in their impacts on BESs (Figure 3). Waterlogging oversaturates soil with water, promoting anaerobic conditions and causing unhealthy plant roots, which in turn reduce nutrient uptake and crop growth. Some of the well-documented mechanisms for reducing crop growth include stomatal closure, which is necessary for gas exchange (Rodríguez-Gamir et al. 2011); induces oxidative stress, which decreases the activity of critical enzymes like ribulose-1,5-bisphosphate carboxylase and phosphoenolpyruvate carboxylase (Muhammad et al., 2021); reduces chlorophyll that is essential for carbon dioxide (CO_2) assimilation and photosynthesis in plants; accumulation of gases like ethylene, CO_2 and reactive oxygen species at plant roots (Niu et al., 2023) as well as chemical imbalances (Bhaduri et al., 2017). For example, gas accumulation damages cellular components, such as chloroplasts, thereby limiting the plant's photosynthetic capacity (Ren et al., 2016). Low oxygen levels around the root zone affect nutrient uptake by limiting nodulation and nitrogen fixation. A deficiency of essential nutrients like nitrogen, potassium, and calcium can result in temporary toxicities of certain soil nutrients like iron and manganese that are typically harmless under well-drained conditions but transform into free ions when the soil's reduction potential is elevated (Najeeb et al., 2015; Fukao et al., 2019; Manik et al., 2019; Kaur et al., 2020; Aslam et al., 2023). These effects can adversely affect soil biota and plant health, thereby disrupting nutrient cycling and soil processes essential for maintaining soil health. It can affect other ESs, such as water purification and climate regulation, through increased atmospheric emissions and leaching of water-soluble nutrients into the soil.

Excessive soil moisture can also increase the risk of plant disease and insect infestation. The selective pressure of anaerobic conditions can reduce the genetic diversity of soil microbes, favoring species and strains, e.g., by increasing denitrifying bacteria and methanogens that can survive or thrive in such environments, and by declining aerobic decomposers and nitrifiers. Specifically, waterlogging supports anaerobic bacteria, such as the Anaerolineaceae family within the Chloroflexi *phylum* and *Geobacter* species in the Proteobacteria *phylum.* Certain fungi and aerobic bacteria, such as those in the *genus Nocardioides* within the phylum Actinobacteria and *Chthoniobacter* within the phylum Verrucomicrobia, are more abundant in drained areas (Gschwend et al., 2020). These bacteria thrive in low-oxygen environments, which are typical during waterlogged conditions. The microbial shift can disrupt plant-microbe interactions, reduce plant biodiversity, and alter the genetic pool and diversity of soil fauna, such as earthworms and nematodes, that rely on aerobic conditions and are essential for nutrient uptake and plant health. Ultimately, ecosystem services, such as nutrient cycling, soil formation, and pest and disease regulation, are affected. For example, waterlogged conditions promote the growth of pathogenic microbes such as *Pythium, Phytophthora*, and *Fusarium* spp, which thrive in wet/anaerobic conditions (Tyagi et al., 2024). These pathogens can increase plant vulnerability and worsen the severity of root rot and damping-off diseases. They weaken the plant's immune responses and reduce its resilience to other environmental stresses.

Source: Ojo et al., 2011

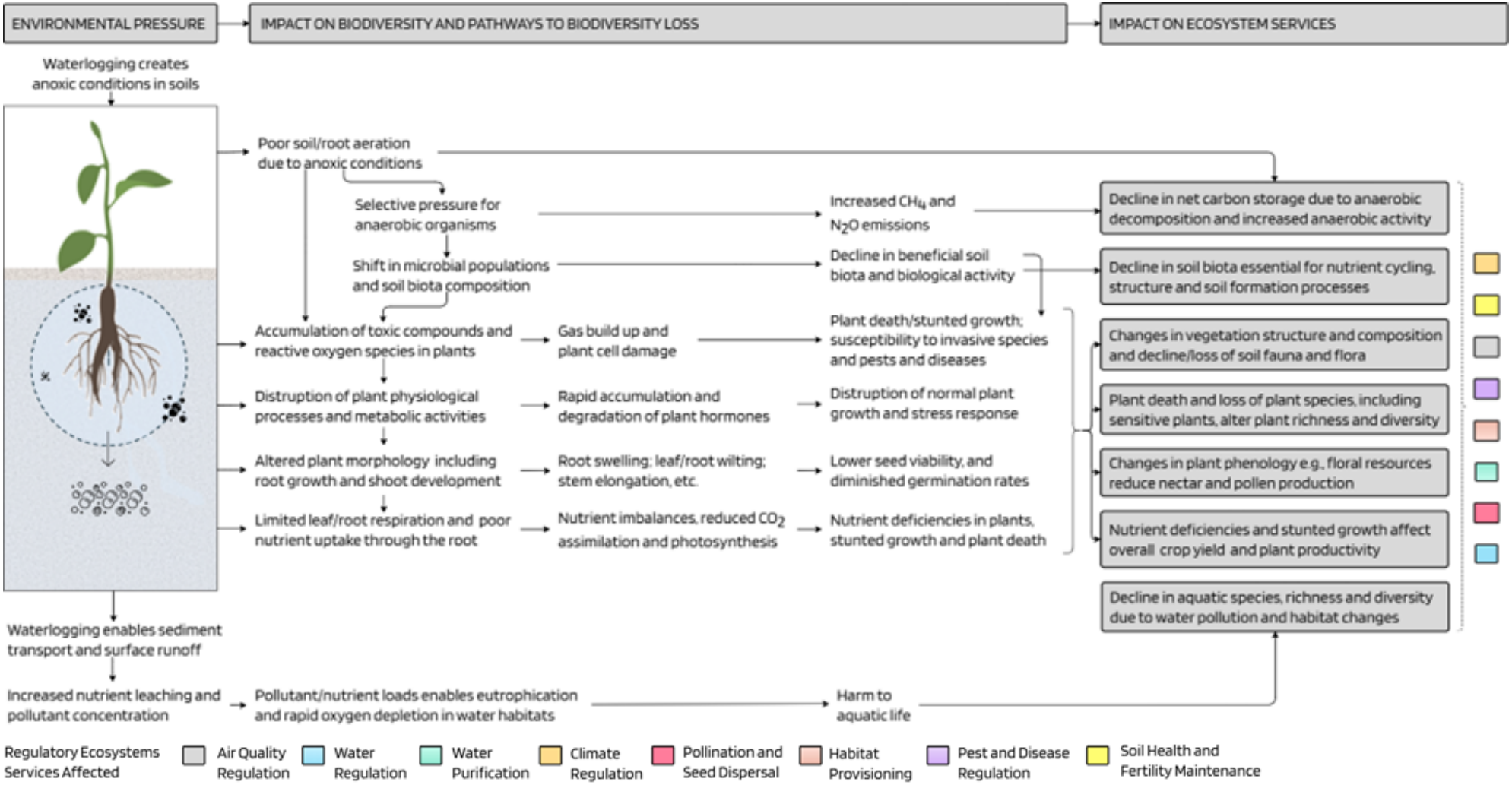

Figure 3 *− An illustration of waterlogging's primary impacts on soil ecosystems and plant physiological processes.*

Source: Tosin Somorin/IWMI

Box 2: Soil Salinization Impacts

Waterlogging often coincides with soil salinization, and their combined effects are more harmful to crop yields than their individual effects (Kahlown et al., 2002). According to FAO 2021a, approximately 424 million hectares of topsoil (0–30 cm) and 833 million hectares of subsoil (30–100 cm) globally are affected by salinity. Approximately 34 million hectares of irrigated land worldwide are affected by salinization, representing approximately 11% of the global irrigated area. Out of this, 77% of the affected land is in Asia, with notable salinity issues in regions such as Pakistan, China, and India.

The large-irrigation-induced causes of soil salinization include water leakages from poorly lined canals and reservoirs, excessive water application, inadequate drainage, and deep percolation into saline aquifers. Salinization in deep percolation contexts occurs when the water table rises within 2 m of the soil surface, and excess salts build up in soils, around crop root zones, and within plant tissues due to capillary action. Salinization is particularly common in arid and semi-arid areas where excessive irrigation and limited rainfall lead to salt accumulation in the soil (Singh et al., 2012). More than two-thirds of salt-affected climatic zones are located in arid and semi-arid areas (FAO, 2021a). Specific causes of salinization in irrigated lands in dryland include the use of saline or brackish water for irrigation, seawater intrusion or salt deposition on the soil surface due to capillary rise from a shallow water table, poor drainage facilities, intensive fertilizer and pesticide use, and improper use of deficit irrigation (Singh, 2015; 2016; Mukhopadhyay et al., 2021).

The primary impacts of soil salinization are on soil microbes and plant health (Sritongon et al., 2022). Figure 4 illustrates how salinity affects soil ecosystems and plant physiological processes through the combined effects of osmotic stress, ion toxicity, nutrient imbalance, and disruption of microbial community structure. In the case of the latter, highly saline soils inhibit microbial growth and enzyme activities, such as the abundance of soil bacterial, fungal, and arbuscular mycorrhizal communities necessary for mineralization. It shifts microbial communities by inducing osmotic stress and ion toxicity. Bacterial community structure varies under salinity stress: some bacterial groups (e.g., Proteobacteria, Actinobacteria) increase in abundance, whereas others (e.g., Planctomycetes, Bacteroidetes) decrease in abundance. While some haloalkaliphilic bacteria can thrive in saline soils, others are adversely affected, including heterotrophic bacteria and free-living diazotrophic microbes that fix nitrogen and help stabilize soil organic matter (Zhang et al., 2019; Haj-Amor et al., 2022).

Soil salinization imposes hyperosmotic, oxidative stress, and ion toxicity on plant growth. This happens when excessive salts build up in the root zone, affecting the plant's leaves and ability to take in water and decreasing CO_2 availability for photosynthesis, leading to osmotic stress, wilting, and stunted growth (El Mokh et al., 2014; Muhammad et al., 2023; Atta et al., 2023). It also disrupts nutrient balance in plants, weakening them, reducing fruiting, and degrading forage quality. Soil salinity exceeding 2 dS/m adversely affects sensitive crops, whereas salinity exceeding 8 dS/m severely impairs the growth of most plants and crops (Hassani et al., 2021). The extent of the impact depends on the crop variety and its salt tolerance. Furthermore, crop tolerance to salinity is highly variable (Tanji and Kielen, 2003): while potato and rice are more sensitive to salts at electrical conductivity (EC) of 2-3 deciSiemens per meter (dS/m), barley, wheat, and cotton have higher thresholds (6-8 dS/m). Many crops are unaffected by salinity but progressively lose tolerance as soil salinity increases. The evolution of salt tolerance has a greater impact on native species' tolerance to other stressors than on invasive species (Liu et al., 2019). For example, Elsey-Quirk et al. (2024) showed that native tree species died or experienced severe dieback in saline environments. This results in the replacement of native species by salt-tolerant exotics and weeds (Briggs and Taws, 2003). The feedback loop of vegetation loss and rising salinity worsens over time.

In addition to direct effects on soil microbes and plant species, salinity can increase soil sodium content, thereby reducing the stability of soil aggregates. It can affect the overall functioning of the soil ecosystem, diminishing habitat for terrestrial species and contributing to biodiversity loss at multiple levels. According to Castillo et al. (2017), changes in community structure can modify food-web interactions, including species interactions and trophic positions. In terrestrial ecosystems, salinity significantly affects soil invertebrates. Sensitive organisms such as potworms (*Enchytraeids*) experienced an immediate population decline under high salinity due to physiological stress and delayed recovery even after salinity was reduced (Pereira et al., 2018), highlighting a potential long-term reduction in trophic diversity. Generally, increasing salinization negatively affects trophic diversity, depending on organisms' salinity tolerance, and can alter the structure and function of freshwater ecosystems, for example, by affecting reproduction, osmoregulation, and survival. Microinvertebrates (such as *Hydra* spp.) are reported to be more sensitive to salinity than vertebrates (Castillo et al., 2017). Aquatic insects, scrapers, gatherers, and filterers show greater sensitivity to salinity than omnivores. The various impacts can affect nutrient recycling and the regulation of disease and climate, as well as supporting services such as habitat maintenance that sustain plant and animal richness.

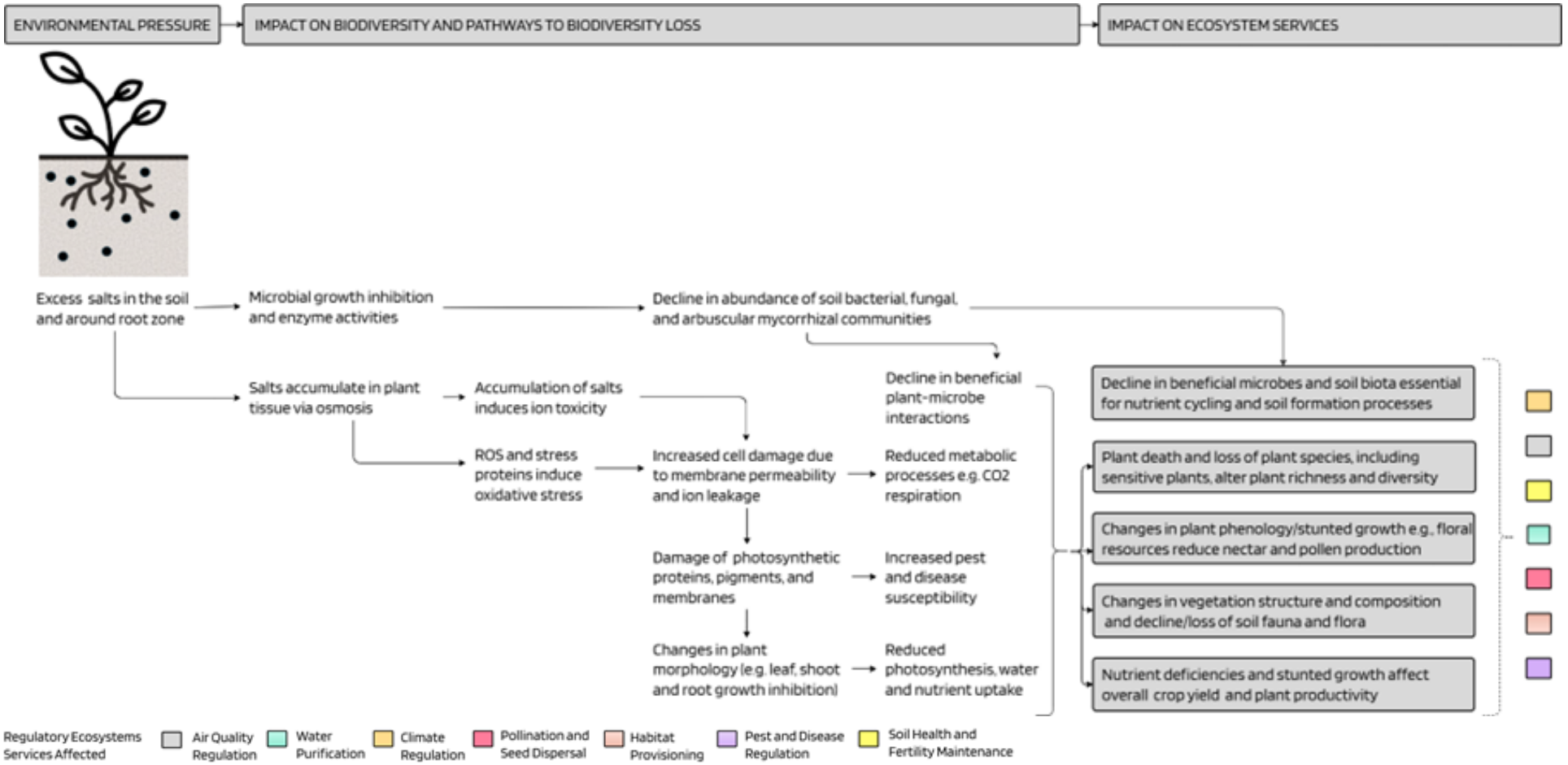

Figure 4 *− An illustration of soil salinization impacts on soil ecosystems and plant physiological processes.*

Source: Tosin Somorin/IWMI

3.1.2. Poor Scheduling of Irrigation Water

Poor irrigation scheduling may be due to unsuitable plans, imprecise soil water measurements, errors in water balance modeling, and uncertainty about the amount of water applied during each irrigation. In many cases, irrigation is not well timed with respect to land and soil characteristics, and farmers often lack specific knowledge of the water requirements of different crops. The costs and complexity of in-field soil-moisture measurement devices, high electricity costs, and limited access to accurate weather forecasts and soil-moisture information can also pose barriers for many farmers, alongside institutional, cultural, and policy issues (Knox et al., 2011; Yohannes et al., 2019). Ultimately, poor irrigation scheduling results in either under- or over-watering. Box 3 focuses on the effects of induced water stress from under-irrigation, as the effects of waterlogging have been discussed earlier. The effects of induced water stress due to water over-abstraction and climate change are discussed in sections 3.2 and 3.4, whereas those related to crop and land management are in Part 2 of this report.

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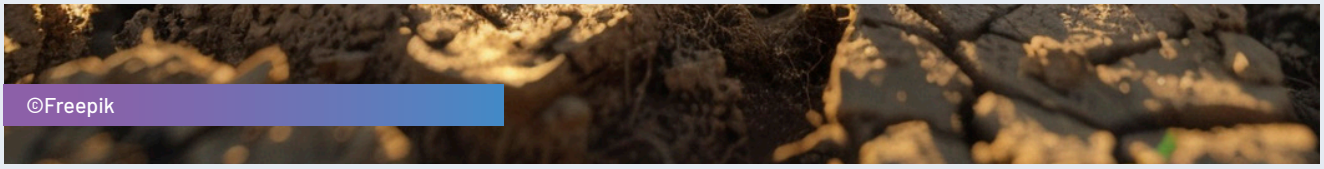
Box 3: Induced water stress impacts

There is limited evidence regarding the broader impacts of induced water stress resulting from under-irrigation. In many arid and semi-arid agroclimatic conditions, deficit irrigation is intentionally practiced to reduce water use and optimize water productivity. However, both intentional and unintentional irrigation practices induce water-deficit stress. Our findings show that the primary impacts are on soil biodiversity and ecosystems. Water deficit reduces moisture conditions and significantly alters the structure, functioning, and processes of soil ecosystems, including root growth, soil carbon storage, and the structure and function of microbial communities (Dangi et al., 2016; Natasha Abdul Rahman et al., 2021). Soil water deficit can reduce plant cell turgor, thereby limiting leaf area development, plant height, and photosynthetic efficiency (Meshram et al., 2021). For example, in cotton, it resulted in low fruit retention and a significant decline in seed-cotton and lint yields. Water-deficit conditions dehydrate plant tissues, leading to an imbalance between root water uptake and leaf transpiration (Ahmad and Li, 2021). These impacts can reduce crop yields and degrade soil health (Rodrigues and Pereira, 2009). Figure 5 illustrates how induced water stress can adversely affect plant physiological processes and soil ecosystem processes, and how these effects subsequently impact BESs.

Evidence shows that several below-ground processes, including carbon cycling and nutrient accumulation, are affected by water-deficit conditions (Flynn et al., 2021). These conditions alter soil microbial populations, which are important in making nutrients available to plants and supporting soil formation and processes. Specifically, there is a noticeable change in the compositions of bacterial and archaeal communities, and drier soils have fewer beneficial soil microbes, such as arbuscular mycorrhizal fungi. Shifts in microbial community composition significantly affect soil microbial biomass by disrupting nutrient pools and inter-kingdom interactions in the plant rhizosphere (Wang et al., 2021, 2022). For example, studies by Rodriguez-Ramos et al. (2022) found decreases in overall microbial biomass and in specific microbial populations, such as soil eukaryotes, under deficit irrigation. Changes in soil moisture levels in tomato plots affected the metabolic capabilities of microbial communities related to carbon and nitrogen, which are vital for both soil health and plant growth. Therefore, an imbalanced soil microbial community can disrupt soil biogeochemical processes and reduce the availability of essential nutrients such as nitrogen and carbon, ultimately affecting plant growth and soil fertility.

The influence of crop productivity varies among plant species, depending on their physiological and structural adaptations. Plants with extensive root systems and efficient water-absorption patterns can draw water from deeper soil layers to meet their transpiration demands and sustain growth and yield. Drought-resistant plants can mitigate yield declines by altering root thickness, depth, and penetration capacity. Increasing root mass under water-deficient conditions can increase aboveground biomass production, and higher carbon inputs at the root level can enhance soil organic carbon formation. However, similar water deficiency can adversely affect biomass production (Yi et al., 2010), particularly for crops like *alfalfa* that require substantial water inputs (Li et al., 2023). The varied impacts underscore the importance of carefully managing water-deficit practices. Information on the loss of other important ecosystem services due to poor irrigation scheduling is scarce and fragmented. However, an inference can be drawn from the impact of reduced biomass production on ecosystem services, e.g., by reducing habitats and food available to various organisms. Moderate deficit irrigation may reduce certain plant diseases, such as root-knot nematode infections (Rodriguez-Ramos et al., 2022), which could be a potential benefit. However, overall ecosystem balance may be disrupted by changes in predator-prey dynamics among soil microorganisms, with broader ecological implications. The trade-off between water-use efficiency and crop productivity can also affect crop productivity, potentially leading to changes in land-use patterns and agricultural practices and impacting local ecosystems.

Water-deficit conditions may exacerbate soil salinization and sodification, particularly when crops are grown in arid and semiarid areas and low-quality (saline) water is used for irrigation (Aragüés et al., 2014; Toumi et al., 2024). Soil salinity is induced by inadequate leaching and salt accumulation. The impact on crops depends on initial soil and water salinity level, irrigation method, soil texture, and climatic conditions, particularly the amount and timing of precipitation during non-irrigation periods. The studies mentioned above did not show any long-term adverse effects on soil quality, and various deficit irrigation methods did not significantly impact crop yield and productivity. However, concurrent water and salinity stress adversely affected the growth and yield of other crops, such as alfalfa (Qiu et al., 2021), resulting in reduced aboveground dry matter and species diversity. This was achieved through osmotic effects and by inducing specific ion toxicities. The previous section already presented the impacts of soil salinization; the effects of using low-quality water are presented in the next section.



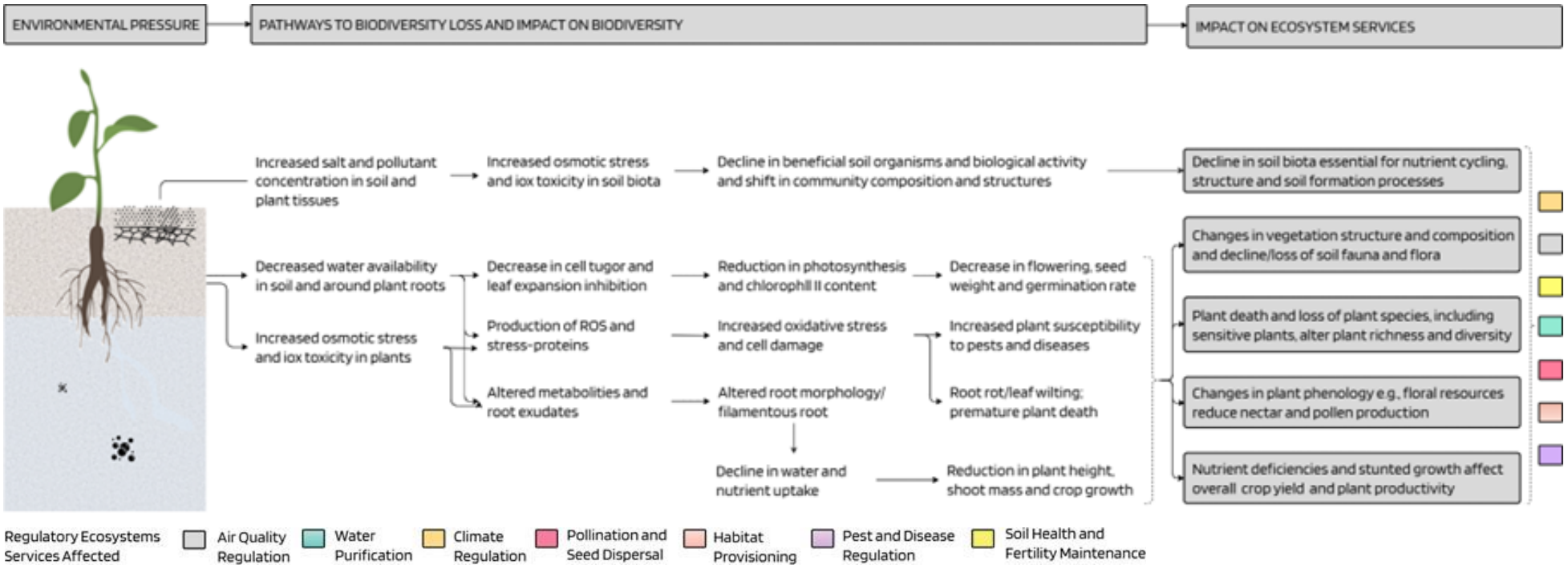


Figure 5 *− An illustration of the primary impacts of induced water stress on plant physiological processes.*

Source: Tosin Somorin/IWMI

3.1.3. Poor Quality Water for Irrigation

Water is becoming increasingly scarce worldwide, both in quantity and in quality. As a result, farmers worldwide are increasingly turning to low-quality water, such as saline water or wastewater with high salt and contaminant concentrations, for irrigation. In dry climates where water is scarce, direct use of treated, untreated, or partially treated wastewater for irrigation is typical (Dreschel et al., 2010. More prevalent than direct use is the indirect use of diluted wastewater from untreated or partially treated urban sources, mixed with stormwater and freshwater in drains and streams (Keraita et al., 2008; Jiménez et al., 2009). For example, in places such as Vietnam's Red River Delta and Pakistan's Haroonabad, wastewater is pumped into irrigation canals to supplement freshwater, often the only water available during dry seasons (Jiménez et al., 2009; Dreschel et al., 2010).

In India, areas of Punjab, Haryana, Delhi, Maharashtra, Gujarat, Uttar Pradesh, and Rajasthan, primarily in dry and semi-arid regions, use low-quality saline water for cropping, which has led to salt accumulation. High sodicity is evident in areas such as Rajasthan, Haryana, and Uttar Pradesh (Tripathi et al., 2011). Many aquifers in Bangladesh, India, and Pakistan are affected by elevated concentrations of iron, manganese, and arsenic (Das, 2022; Islam & Mostafa, 2024). Extensive regions of Rajasthan, Orissa, and parts of Andhra Pradesh, Telangana, and Karnataka are known to have groundwater contaminated with fluoride (Subba Rao et al., 2020; Das, 2022. The combination of high temperatures and low rainfall in certain areas exacerbates soil salinization, leading to even higher salt concentrations. It is estimated that more than 154,000 km² of agricultural land in South Asia may be irrigated with groundwater exceeding the WHO guideline value of 10 µg/l (WWQA, 2021). The impact of soil salinization is discussed under poor irrigation water management. Box 4 buttresses the effects of increased salinity on water permeability and soil acidification.

Box 4: Salinity impacts soil compaction and water permeability

Increased soil pH, salinity, and exchangeable cations (e.g., Na^{+}, Ca^{2+}, Mg2+) are common effects of irrigation with poor-quality water (Al-Omran et al., 2010; Marlet et al., 2009). Irrigating with such water can have several detrimental effects on soil structure and fertility. For example, the accumulation of salts can result in reduced saturated hydraulic conductivity, which impairs water infiltration and drainage; increased concentrations of sodium can cause soil dispersion, reducing soil aggregate stability, especially in acidic and low clay-content soils (Becerra-Castro et al., 2015; Aram Ali et al., 2019; Nick et al., 2024. Evidence shows that soil structure deteriorates, bulk density increases, and infiltration rates reduce when water with a high sodium adsorption ratio is used for irrigation, especially when followed by low-salinity water application (Bethune & Batey, 2002; Emdad et al., 2004. Soil pores can become blocked, limiting the downward moisture percolation and solute transport. This can negatively affect root growth, hinder the development of beneficial soil microorganisms, diminish habitats for small invertebrates, and restrict nutrient availability. Additionally, wastewater rich in suspended solids can clog soil pores, reducing water infiltration (Becerra-Castro et al., 2015; Ofori et al., 2021). This can increase agricultural runoff of nutrients (N, P, K), xenobiotic compounds, and other contaminants into water bodies. Increased salinity can alter soil physical properties, e.g., by reducing hydraulic conductivity and impeding leaching of harmful salts through the root zone. This can also cause groundwater contamination through the downward flux of contaminants. For example, in Varanasi, India, the groundwater supplies are found to be contaminated with pharmaceuticals and pesticides such as sulfamethoxazole (<0.001−0.034 µg/L) and perfluoroalkyl substances (<0.0001−0.033 µg/L) due to untreated wastewater irrigation (Lapworth et al., 2017). All of the above environmental changes, along with contaminants (heavy metals, emerging contaminants, pathogens, and nutrients), can affect soil biodiversity and ecosystem functions, including decomposition rates, nutrient retention, soil formation, and nutrient cycling. These functions are needed for clean water, pest and pathogen control, soil fertility and crop production, and climate change mitigation. For example, high salinity can reduce root exudate production, thereby decreasing microbial biomass. It can increase the solubility and bioavailability of heavy metals in soil, thereby increasing plant uptake and accumulation. It can lead to toxicity for both macro- and microorganisms, affecting microbial activity and diversity, including important bacterial strains such as *Rhizobium leguminosarum* (Minhas et al., 2022). Additional note on the impacts of pollution is provided in Part 3 of this report.

3.2. Over-abstraction of groundwater and surface water

3.2.1. Over-abstraction for irrigation

Global freshwater use, which includes withdrawals for agriculture, industry, and municipal purposes, has surged from 500 billion m³ to almost 4 trillion m³ since the 1990s (Ingrao et al., 2023. Approximately 70% of this withdrawal is linked to agriculture, primarily for irrigation, livestock, and aquaculture. The rest is used for industrial and domestic purposes (Ritchie et al., 2023. Some of the major agricultural production centers that rely heavily on irrigation are in North India, the Indus River Basin in Pakistan, the North China Plain, and the Central Valley in California (Paria et al., 2021; Liu et al., 2022; Sajid et al., 2024; see Figure 6). Among countries with significant irrigation schemes, India and Pakistan have the most unsustainable expansion, with 86% (12.1 Mha) and 87% (1.53 Mha) of gross expansion occurring in areas with blue water stress[4] (Mehta et al., 2024).

Some notable examples of unsustainable groundwater extraction are cited in India, where extensive irrigation schemes backed by government subsidies in the form of free energy incentives (Sidhu et al., 2020 led to accelerated groundwater extraction. This led to significant water wastage, lowered water levels by 8 meters (compared to 1980 levels, and continued to amplify the harmful effects of climate change (Sishodia et al., 2017; Tack et al., 2017). Other examples are also cited in the Indus River of Pakistan, where extensive irrigation practices have diminished fish populations (Braulik et al., 2014; high water withdrawals from the Nile and Indus Rivers, primarily for irrigation, have led to seawater intrusion upstream, affecting the positions of estuaries and riverine delta ecosystems (Kidwai et al., 2018; excessive groundwater withdrawals in arid and semi-arid regions of Africa and Asia, where annual evaporation and transpiration exceed rainfall and surface water storage options are inadequate, have depleted aquifers, lowered water levels in streams and lakes, deteriorated water quality, and led to land subsidence (De Graaf et al., 2019; Jasechko et al., 2024.

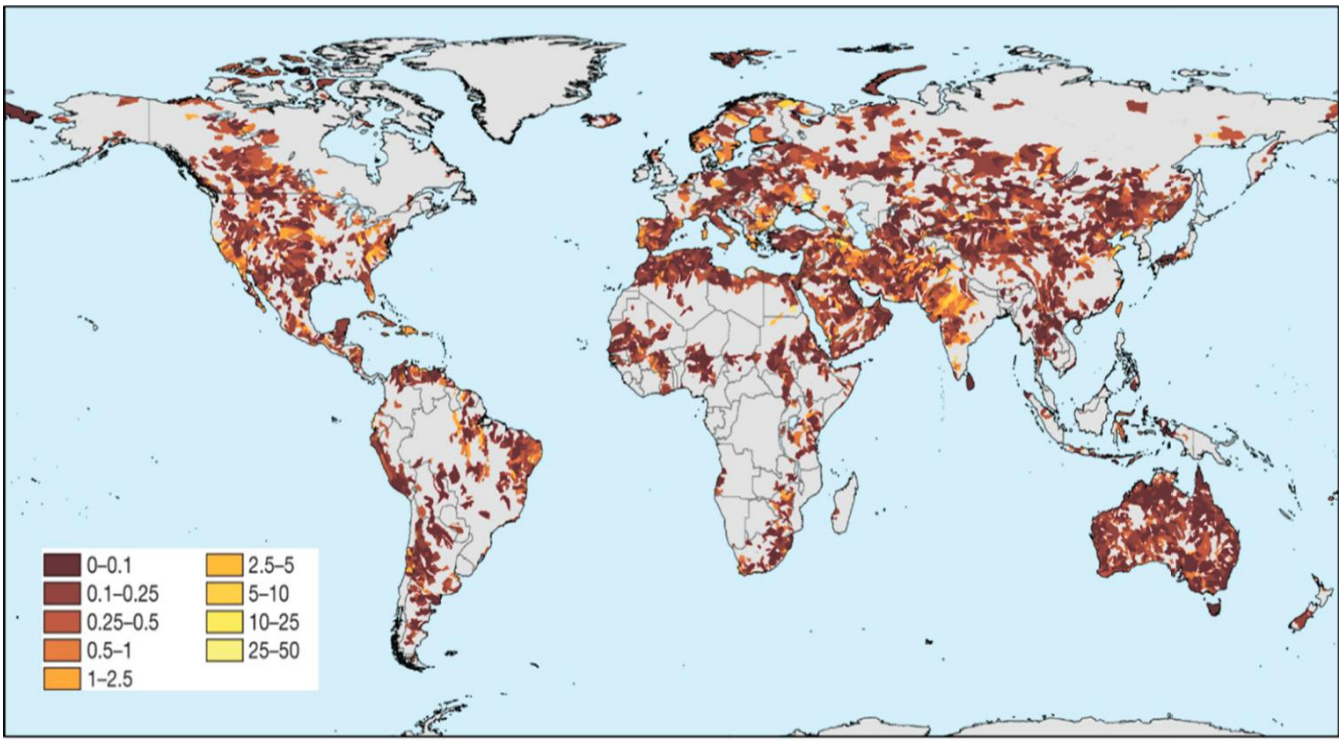


Figure 6 - *A global map of areas with estimated head decline caused by groundwater pumping and associated with reaching the environmental limit (De Graaf et al., 2019)*

[4] conditions where there is not enough renewable surface and groundwater available to meet the demand for irrigation water.

Credit: Mohamed Khettouch/Pexels

3.2.2. Over-abstraction for livestock production

Livestock and milk production have increased dramatically over the past 60 years. Livestock production has grown at an annual rate of 2.7%, reaching an estimated 361 million tons in 2022, corresponding to ~45 kg per capita. Similarly, milk production has increased by 1.7% annually, totaling ~930 million metric tons in 2022, corresponding to about 117 liters per capita (FAOSTAT 2024). According to FAO AQUASTAT, the estimated global water withdrawal for livestock watering is around 31 km³/year, accounting for around 2% of total water withdrawals for livestock production. The remainder is to produce livestock feed, including cereals, such as maize, as well as rainfed and irrigated pastures and grazing lands. Heinke et al. (2020) estimate that the annual water use for global livestock feed production is approximately 4,387 km³, accounting for around 41% of total agricultural water use. Producing one calorie of animal-based food typically requires more water than producing plant-based food products (Mekonnen & Hoekstra, 2010). Given the rapid growth in livestock production, the over-extraction of water from aquifers and water bodies is becoming an increasingly significant issue, particularly in regions with intensive feed-based livestock systems that depend on local irrigated pastures, maize, or other animal feeds (Schlink et al., 2010). The risk of water over-extraction related to livestock varies considerably by region, influenced by the spatial distribution of livestock and feed production systems, local water resource conditions, and competing water demands from other sectors. A global assessment by Leng & Hall (2021) identifies hotspot regions in which livestock water supply significantly contributes to unsustainable water use. These regions include northern India, the Middle East, northern China, and the central United States (Figure 7). There are also extensive areas where water over-extraction is jointly caused by both livestock and non-livestock activities. These findings emphasize the necessity for integrated water management.

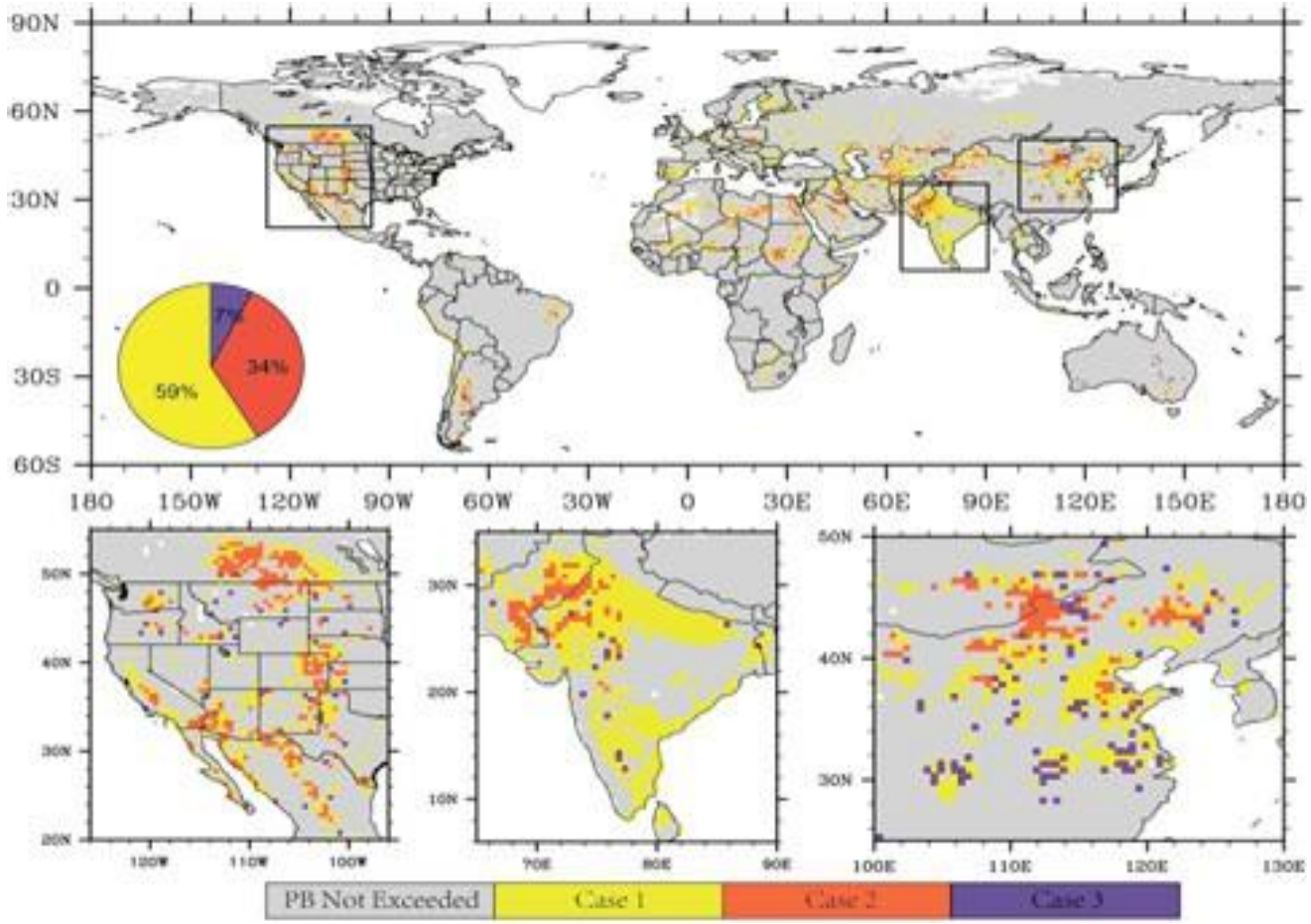


Figure 7 - *The state of water planetary boundaries (PB) for the globe and three hotspot regions. Grey: water PB not exceeded. Yellow: PB exceeded due to non-livestock water use (case 1). Red: PB exceeded both by non-livestock water use and by livestock water use (case 2). Purple: livestock water use has been responsible for tipping over the PB (case 3). Calculations are made for each year, and the long-term mean is shown. The pie plot shows the percentage areas of each case (Leng and Hall, 2021).*

While the specific uses, irrigation for agriculture or water supply for livestock, might differ, the impact of over-abstraction of freshwater resources remains the same. Evidence indicates that the primary impacts center on reduced water availability, disruption of natural water cycles, and changes in habitat structure (Rolls et al., 2012; Rolls& Bond, 2017; Lapides et al., 2022). Box 5 jointly discusses the primary impacts of over-abstraction of freshwater for irrigation and livestock production, focusing on the effects of groundwater and streamflow depletion on hydrological and ecological processes and on the deleterious consequences for riparian and aquatic ecosystems, irrespective of water use. The effects on water quality and the ecological integrity of freshwater ecosystems are discussed only briefly, but detailed information is provided in Part 3 of this report. This includes information on how the specific uses of freshwater for irrigation in agrochemical-intensive monocultures or intensive livestock production systems contribute to water pollution.

Box 5: Impact of water over-abstraction on riparian and aquatic ecosystems

Excessive abstraction of groundwater and surface water can reduce groundwater recharge (Döll et al., 2012). Similarly, when groundwater is extracted at a rate exceeding its natural recharge, river baseflow can decline, reducing natural streamflow (Castaño et al., 2018). Depletion can occur in two ways: first, when groundwater extraction intercepts water that would otherwise flow into a stream, and second, when altered groundwater flow promotes seepage losses into the aquifer (Barlow and Leake, 2012). The effects are complex and particularly significant in regions with strong hydraulic connections between aquifers and streams (Barlow & Leake, 2012; Dangar et al., 2021). Research by de Graaf et al. (2019) has shown that streamflow has fallen below necessary levels for environmental flows in 15–20% of watersheds experiencing intense groundwater extraction. Projections suggest that by 2050, up to 80% of these watersheds will be unable to sustain environmental flows if current development and climate change trends continue. Such a reduction in environmental flows can sever habitat connectivity and negatively impact the ecological integrity and resilience of riparian and aquatic ecosystems (Jasechko et al., 2023).

The mechanistic links between low flows and changes in ecological structures and functions of riparian and aquatic ecosystems are attributed to one of four environmental pressures: reduced water habitat, water quality changes, disrupted energy and nutrient transport, and disrupted connectivity and refugia dependency (Ingrao et al., 2023; Rolls et al., 2012; Lapides et al., 2022). Low streamflow can limit the size of aquatic habitats[7]. This can manifest as reduced water volume, area, and depth, and as changes in river velocity, including variations in fast-flowing riffles and floodplains. Modifications to streamflow characteristics can affect flow magnitude, frequency, timing, variability, and overall water quality (Naiman et al., 2008; Lapides et al., 2022). These changes can influence the composition of biota, trophic structures, and the carrying capacity for aquatic organisms, particularly fish and macroinvertebrates that depend on flowing-water habitats. Additionally, lower stream flows can heighten competition and predation risks. The extent of the impact will depend on the interactions between local hydrology, geomorphology, and changes in hydraulic conditions (Rolls et al., 2012; Rolls and Bond, 2017).

Low water flows can affect aquatic organisms by impairing water quality, for example, by increasing sedimentation and concentrating pollutants. Several fish populations, such as brook trout (Salvelinus fontinalis), are sensitive to low dissolved oxygen levels during periods of low water flow. Additionally, certain macroinvertebrates are sensitive to high thermal/electrical conductivity (Calapez et al., 2017; Su et al., 2019; Hyvärinen et al., 2022). This can reduce oxygen levels, creating hypoxic conditions. It can sever connections between surface and groundwater and among aquatic organisms, thereby increasing similarity among aquatic assemblages (Rolls et al., 2012). Furthermore, low flows can influence the sources and transport of materials in river ecosystems, for example, by decreasing the movement of organic matter and nutrients and reducing food availability for higher trophic levels (Rolls et al., 2012; Munn et al., 2018). This includes the longitudinal transport (continuous movement) of energy and organic matter in streams, the lateral transfer of energy between river channels and surrounding riparian and floodplain areas, and the vertical flow of nutrients connecting benthic substrates, groundwater, and surface waters. In these contexts, low flows can retard longitudinal energy flow, for example, by retaining benthic organic matter upstream. Fish may experience reduced growth at both the individual and population levels due to decreased energy intake during low-flow periods. These declines can reduce the transfer of energy from terrestrial or riverine sources to higher trophic levels. Diminished lateral connections in intermittent streams can also affect the primary energy sources (autochthonous versus allochthonous) that support aquatic food webs. Lower production within aquatic systems because of low (or diminished) flow can also influence the productivity of riparian and terrestrial ecosystems and their inhabitants. Furthermore, increased accumulation and retention of fine sediments during low-flow conditions can impede nutrient transfer from benthic substrates, groundwater, and hyporheic zones, thereby affecting ecosystem productivity and biodiversity.

Ultimately, reduced water flow limits habitat connectivity and diversity, creating separations between rivers and their floodplains and restricting species' ability to migrate within these ecosystems. Limited access to refugia, that is, stable water areas where species can endure harsh conditions during prolonged low-flow periods, can result in declines in local populations, adversely impacting biodiversity over time. These can lead to cascading effects on BESs in river ecosystems. For instance, traits related to dispersal and the availability of refugia significantly influence patterns of biotic diversity across multiple scales during and after low-flow periods. When sensitive species disappear from communities during extended low-flow situations, isolated refugia foster increasingly distinct communities. This could result in a situation in which only generalist, tolerant species remain, producing homogeneous assemblages across refugia. As a result, the diversity and resilience of these ecosystems may be compromised, increasing their susceptibility to additional stressors (Rolls et al., 2012). All these pieces of evidence underscore the importance of maintaining adequate environmental flow to support biodiversity and ecosystem integrity. Figure 8 illustrates how groundwater and streamflow depletion impact riparian and aquatic ecosystems.

Groundwater processes also influence the abundance of riparian vegetation, but limited studies have quantified its role in ecosystem diversity and richness. Most research has focused on terrestrial biomes, particularly in arid and semi-arid landscapes, which may limit our overall understanding of dynamics in riparian and aquatic ecosystems. Current evidence suggests that aquatic and riparian vegetation, particularly in arid regions, is highly sensitive to changes in surface water and groundwater levels, including low-flow periods and groundwater depth (Stromberg et al., 2007). In some cases, riparian flora sequentially "desertifies", with wetland species being the most vulnerable. Changes in the composition, species diversity, and structure of riparian vegetation directly affect habitat quality for wildlife, particularly birds (Merritt & Bateman, 2012). Other impacts on riparian and aquatic vegetation are linked to the role that riparian plants play in filtering pollutants and in sediment retention, stability, and erosion prevention (Land and Peters, 2023). They also play a crucial role in regulating water flows, providing habitat, and serving as food sources. As such, areas with low groundwater discharge are considered less likely to support effective water regulation and purification services or to sustain diverse aquatic species.

In terrestrial landscapes (forests, grasslands, meadows, and woodlands), impacts of changing water depth are observed as shifts in composition (e.g., from water-tolerant to drought-tolerant and xerophytic species), changes in rooting depth, and a decline in floristic quality (Glanville et al., 2023). Subtle differences in water availability or induced water stress may manifest as significant differences in canopy cover, thereby distinguishing vertical layers as woody and herbaceous. This can influence intraspecific competition, survival, nutrient availability, and water use. Vegetation stress and mortality may, in turn, lead to progressive changes in species distributions. For instance, shrubs exhibit limited diversity and lower calcium and magnesium levels, whereas trees prefer reduced salinity. This can adversely affect plant growth, community structure, species diversity, vegetation succession and other organismal processes (Land & Peters, 2023). Other contributing factors include groundwater pH and nitrate and salt concentrations (Glanville et al., 2023).

Excessive groundwater extraction can lead to several secondary impacts, including aquifer compaction, saltwater intrusion, and rising groundwater levels in coastal regions. Aquifer compaction occurs primarily due to over-extraction of groundwater, which decreases the pressure inside the aquifer. This pressure drop can cause the surrounding geological materials to compact, leading to land subsidence. Such subsidence may damage critical infrastructure and increase flood risk (El Shinawi et al., 2022; Borchers and Carpenter, 2014), ultimately affecting key ecosystem services that provide nourishment and regulate environmental conditions. Excessive groundwater extraction is also linked to saltwater intrusion (Jasechko et al., 2020). When coastal aquifers are over-extracted, freshwater discharge to the sea is reduced, lowering the local water table. This condition allows seawater intrusion, which degrades groundwater quality (Alfarrah & Walraevens, 2018). Persistent surface flooding can also cause rising groundwater levels, increasing waterlogging and soil salinization. Recovery rates from these issues are typically slower than the rates of decline. In the long term, essential services for flood regulation, water purification, disease control, and climate stability are adversely affected. Globally, over-abstraction of groundwater has tilted the Earth's axis and contributed to global sea-level rise, further impacting human and planetary health. An estimated 2,000 billion cubic meters of water were extracted from underground storage between 1993 and 2010, which is said to have led to an annual shift in the geographic North Pole of 4.36 cm (Seo et al., 2023). Surface runoff from over-extracted water can degrade soil health and water quality by increasing sediment transport, nutrient and pollutant concentrations, and by altering soil infiltration and water storage capacity (Ponting et al., 2021). This degradation affects vital regulating and supporting services, including habitat maintenance.

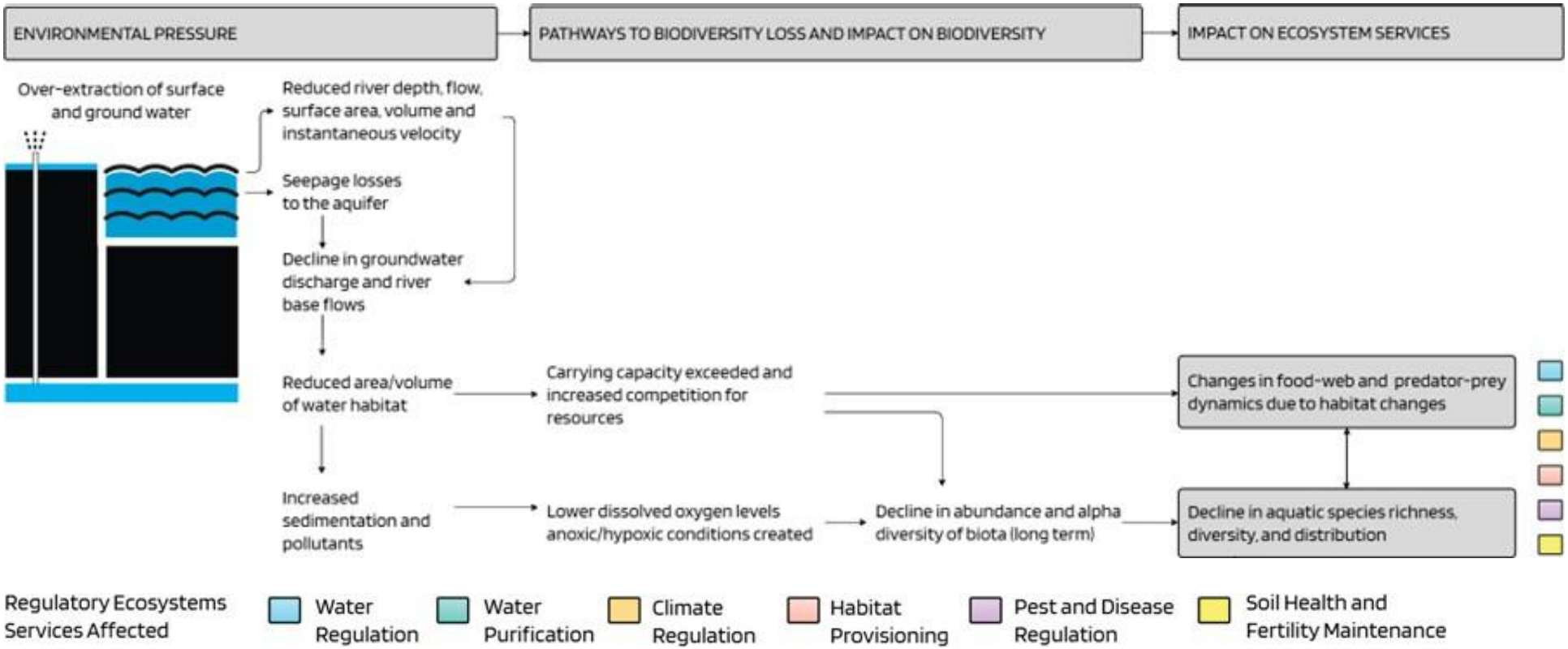


Figure 8 *− An illustration of the impact of groundwater and streamflow depletion on riparian and aquatic ecosystems.*

Source: Tosin Somorin/IWMI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3.3. Watershed Management

Watershed management focuses on the effective management of land, water, and vegetation to conserve natural resources while balancing human and environmental needs. The primary goal is to minimize or mitigate downstream adverse impacts. However, certain management practices can lead to significant changes in land use, such as agricultural expansion into wetlands (e.g., for farming, grazing, or aquaculture); water drainage and diversion of wetlands for irrigation; overexploitation of plants, land, and fish; intensive farming or agricultural activities that increase pollutant loads (Wood and van Halsema, 2008; Chuma et al., 2022; Dixon and Wood, 2003). These practices can disrupt land use and hydrology, particularly in upstream regions, thereby increasing runoff and soil erosion (Wang et al., 2018b). This may heighten the risk of permanent flooding (or inundation) and increase sedimentation in downstream rivers, as upstream and downstream areas within a watershed are typically interconnected through stream flow and sediment transport. Significant land-use changes and hydrological disturbances may directly affect water quality in downstream areas, with effects further influenced by factors such as topography, climate, and geography (FAO, 2023). Some examples are drawn from the Ciliwung watershed in Jakarta, Indonesia, which has experienced hydrological disturbances over the past decade due to land-use activities. Land-use change activities include a 10% decrease in forest cover, an 18% decline in plantations, and a 169% increase in dryland farming, all of which contribute to permanent flooding (Asdak et al., 2018). In Yemen, the over-exploitation of groundwater in uplands due to market-oriented agriculture led to groundwater depletion and reduced streamflow. The construction of storage and diversion structures upstream fragmented habitats for various species and reduced downstream flow, thereby negatively impacting associated ecosystems (Sarah et al., 2008; Ghafouri et al., 2012; Wang et al., 2018b).

This section of the report focuses on wetland drainage and conversion to agricultural land, highlighting the impacts of drainage and the neglect of riparian buffers on BESs. The consequences of mismanagement of large reservoirs and the effects of reliance on constructed storage are also discussed. Earlier sections (3.1 and 3.2) have already outlined the impacts of agricultural water use at the farm/farm systems levels. In contrast, Section 3.3 examines in greater detail the broader implications of agricultural water consumption at the landscape (watershed) level. Issues related to deforestation, overgrazing, and shifting cultivation are addressed in Part 1 of this report, while details on the overuse of pesticides, which can also cause water pollution, are provided in Part 3.

3.3.1. Wetland Drainage and Conversion

Wetlands are among the most productive ecosystems on Earth, covering approximately 1.5−1.6 billion hectares. They provide ecosystem services valued at $47.4 trillion annually (Ramsar, 2018; Ramsar Convention on Wetlands, 2021) and support 40% of global biodiversity across various environments. Wetlands also play other roles, e.g., as critical storage for precipitation and snowmelt, modulating inundation patterns, residence times, and streamflow; areas for nutrient retention and transformation; and habitats crucial for biodiversity, including amphibians, invertebrates, and waterfowl (Evenson et al., 2018). Since the 20th century, 64% of Earth's natural wetlands have been lost, with a persistent annual decline of 1% (Davidson, 2014). The IUCN Red List indicates that 58% of freshwater turtles, 21.7% of fish, 30% of crayfish, 37% of freshwater mammals, and 30% of amphibians are at risk of extinction (Lynch et al., 2023). Wetlands serve as vital habitats and breeding grounds for many of these countless, red-listed plant and animal species, including aquatic insects such as dragonflies and damselflies, as well as various mammals (Darwall, 2011). These ecosystems are characterized by high endemism, evidenced by unique flora and fauna. However, they face significant threats due to limited species migration and their restricted ability to adapt to environmental changes (Wetlands International, 2024). There is an urgent need to preserve and protect these vital wetland ecosystems and the services they provide.

Wetland drainage and conversion occurs in various ways, involving direct processes such as consolidation, where water is redirected from several smaller wetlands into fewer larger ones (McCauley et al., 2015); channelization, where ditches or perforated pipes are used to funnel water away for agricultural purposes or lower water levels in wetlands to enable arable farming (Brown, 1988); and direct water extraction from wetlands e.g., using mechanical pumps when gravity is insufficient (Tavernia et al., 2017). Water can also be indirectly removed by clearing natural vegetation, which reduces water retention and increases runoff (Uwimana et al., 2018). In some cases, embankments/barriers are constructed to prevent further water inflow, and wetland areas can be used directly for farming, as in paddy rice cultivation. These water abstraction and drainage activities can increase sediment transport, erosion, nutrient loads, and pollutant concentrations, ultimately degrading land (Ramsar Convention on Wetlands, 2021). They can also significantly damage wetlands, transforming dynamic hydrological systems into drought-prone or permanently flooded areas. Common examples of wetland loss and degradation worldwide are illustrated in Figure 9. In East Africa, wetlands have significantly declined, with the Anyiko wetland shrinking by 50−55% from 1966 to 2018. Along Lake Victoria, wetlands such as Dunga, Koguta, and Kusa experienced reductions of 50%, 47%, and 34%, respectively, between 1969 and 2000. Uganda's wetland cover lost about 50% during that period, equating to roughly 410 hectares per year (Chuma et al., 2022). In Ethiopia, excessive water diversion for irrigation has led to habitat loss (EWNHS & Wetlands International, 2018). India has experienced significant wetland loss due to agricultural conversion, with 5880 waterlogged areas and more than 77,000 coastal wetlands lost between 2006 and 2017 (EnviStats India, 2022). Overall, Asia and Sub-Saharan Africa have experienced a 40% reduction in wetlands, and Latin America and the Caribbean report widespread ecological deterioration of wetlands (Fluet-Chouinard et al., 2023; Ramsar Convention on Wetlands, 2021). Box 6 highlights the effects of wetland drainage on hydrological connectivity and on the diversity of BESs.

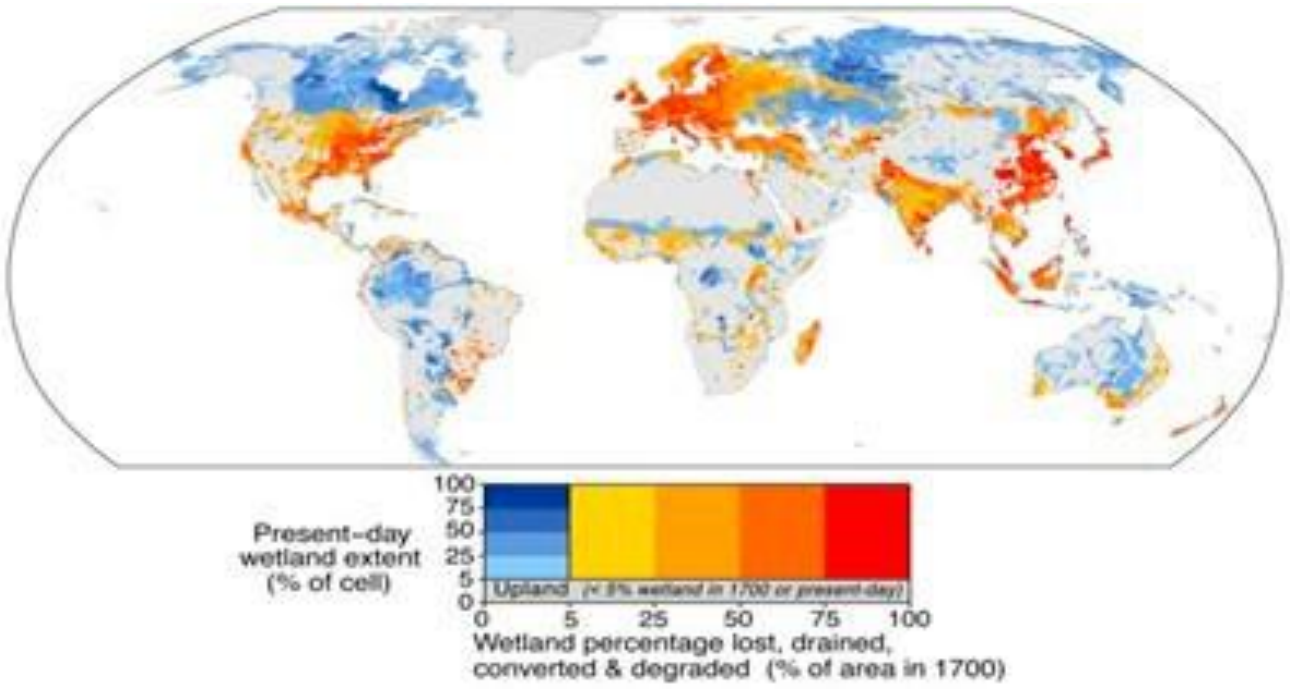


Figure 9 *− Map of cumulative percentage wetland loss as a fraction of wetland cover in 1700*

Source: Fluet-Chouinard et al., 2023.

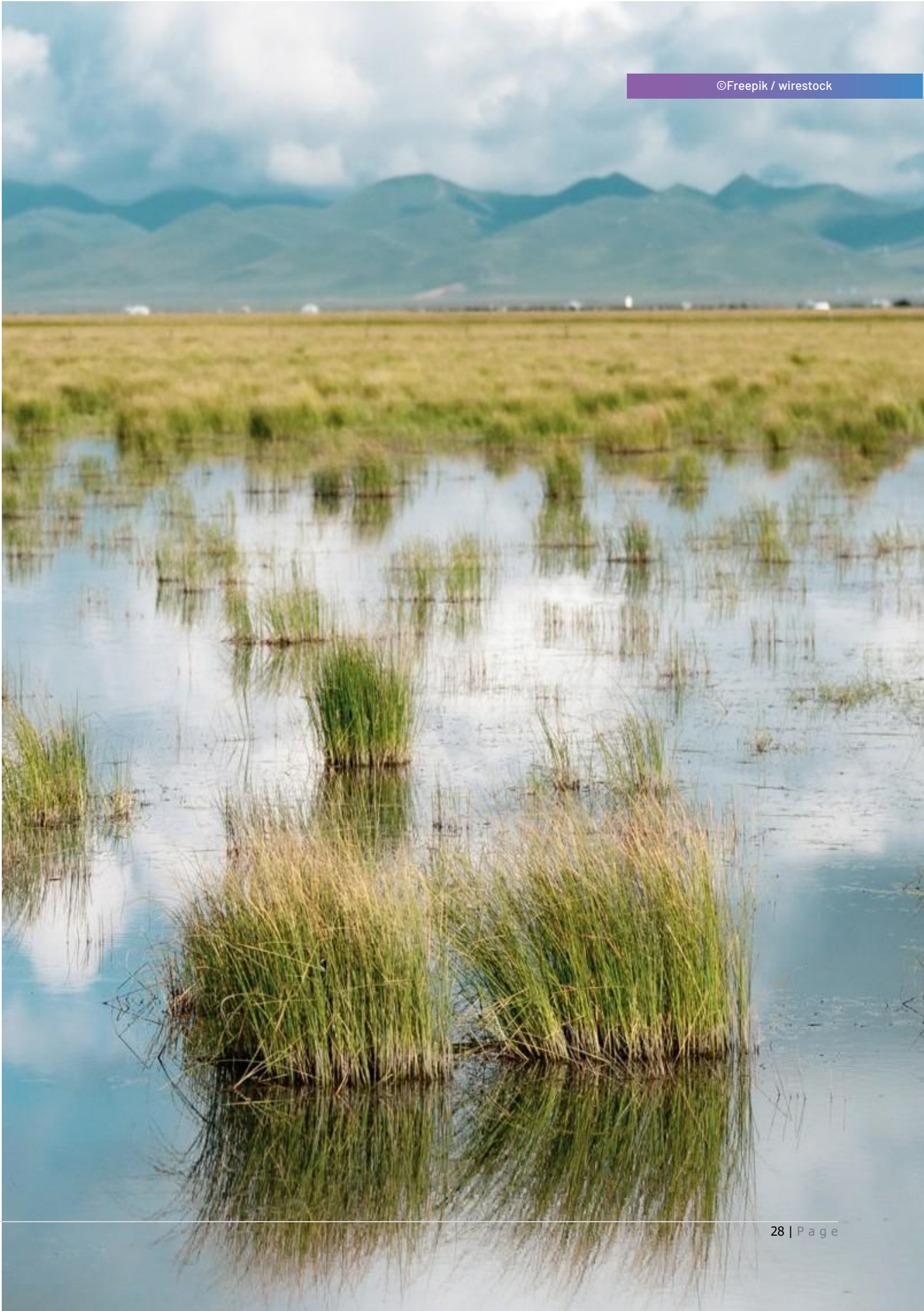
Box 6: Impact of wetland drainage on hydrological connectivity

Wetland drainage through consolidation can significantly alter hydrological connectivity[5] (McCauley et al., 2015) — Figure 10. The risk of loss is related to the size of the wetland. Both small and large wetlands are essential for maintaining balanced hydrological dynamics. They are distributed across landscapes and are crucial in preserving hydrological diversity while facilitating localized connectivity. The loss of these wetlands can lead to cascading effects on watershed-scale processes, resulting in system-wide changes at the catchment and river-basin levels, affecting water flow regulation, sediment transport, and biodiversity (Ramsar Convention on Wetlands, 2021). Small, isolated wetlands are particularly at risk of extinction due to their relatively limited size. When these small wetlands are consolidated into fewer larger ones, their capacity to retain water increases, but this can diminish their ability to store and gradually release water (Evenson et al., 2018). This process leads to the homogenization of hydrological networks and can permanently inundate the hydrological regimes of downstream water bodies. Consequently, increased surface runoff and altered streamflow patterns reduce the wetlands' capacity to mitigate flood risk in the region (McCauley et al., 2015). Furthermore, when small wetlands are drained of resources, they become more susceptible to drying, which can threaten their biodiversity and lead to extinction.

The drawdown of water or other materials, such as peat, from wetlands, or the direct conversion of wetlands to agricultural land, can also lead to considerable alterations in the physical, chemical, and biological characteristics of soils (Minick et al., 2019). When wetlands are drained or converted, the fundamental processes that contribute to the formation of organic soils, such as oxygen and other gas diffusion, are affected. This can influence nutrient mobility and peatland soils, shifting them from anoxic to oxic conditions, accelerating chemical processes such as oxygen diffusion and redox changes, and enhancing nutrient cycling and microbial activity. Increased organic matter decomposition and nutrient mineralization may alter regional carbon storage and lead to nutrient discharge into nearby aquatic ecosystems. Interactions across species in drained wetlands are complex; in the Neotropics, research shows that increased human pressure on freshwater wetlands breaks down the positive relationship between smaller organisms (e.g., protists, phytoplankton, microcrustaceans) diversity and ecosystem services, but the relationship is maintained for larger organisms (fish and macrophytes) (Moi et al., 2022). In the tropical savanna region (the Cerrado of Central Brazil, South America), vegetation diversity is reported to be higher in areas with moderate water-level fluctuations, which reduce dominance by shrubs and fast-growing woody species such as *Miconia albicans* and *Pleroma stenocarpum* (Guilherme et al., 2022). Overall, biodiversity, measured by species richness, was higher in non-drained regions, whereas total density and dominance were greater in drained areas. Another study observed that prolonged high water levels can kill terrestrial and emergent vegetation species such as cattails (*Typha* spp.) and reeds (Phragmites *australis*), which provide vertical structure and habitat for other organisms, whereas excessive drying periods can prevent submerged species from thriving (Orsholm & Elenius, 2022). These alterations can simplify plant communities, reducing habitat heterogeneity and the complexity required to support other organisms, such as insects and birds, and leaving fewer microhabitats for wetland-dependent plants and animals.

Invertebrates such as chironomids (non-biting midges) and dytiscids (diving beetles) respond to changes in wetland hydrology, particularly water drainage (Orsholm & Elenius, 2022). These organisms thrive in wetlands with prolonged hydroperiods, as their larvae rely heavily on standing water for development. However, unexpected and prolonged droughts, as well as permanent deep waters, can drastically reduce their populations and disrupt existing food chains, since they serve as crucial prey for aquatic and terrestrial species (Chastant et al., 2018; Faragó & Hangya, 2012). Moreover, extended hydroperiods can adversely affect many amphibian species, leading to the permanent colonization of fish and increased predation pressure. This dynamic can significantly reduce the richness of both invertebrate and amphibian populations. Extreme fluctuations in water levels, or consistently high water levels, can also reduce habitat diversity, creating challenges for wetland bird species in foraging and nesting. For instance, persistent deep water may limit access to shallow feeding zones, whereas prolonged flooding can destroy nests and reduce ground cover for wading and dabbling birds. Additionally, high water levels can restrict vegetation that provides protective cover and habitat for birds, thereby further diminishing species richness (Orsholm and Elenius, 2022; Malekian et al., 2022; Francis et al., 2021). Overall, altered hydrological regimes that are overly stable or exhibit extreme fluctuations can simplify wetland ecosystems, increase predation pressure, reduce available refuges, and restrict habitat options. These disruptions can threaten the delicate balance of wetland biodiversity. The loss of biodiversity in wetlands affects ecosystem services, including food provisioning, water quality, carbon balance, and groundwater recharge (IPBES, 2019). Multitrophic species in these areas are vital for ecosystem functioning and provide essential benefits. For example, declines in species richness and functional diversity can reduce ecosystem functions related to biomass production, water quality, and nutrient cycling (Moi et al., 2022). Ecological theory supports that multifunctionality enhances ecosystem functions through species complementarity. This means biodiversity and various wetland habitats, regulated by habitat heterogeneity, are essential for sustaining species diversity, maintaining ecological processes, and regulating ecosystem processes.

[5]Function of the landscape to promote or prevent the movement of substances"- a key indicator for protecting biodiversity and maintaining the stability and integrity of ecosystems (Wu et al., 2023).



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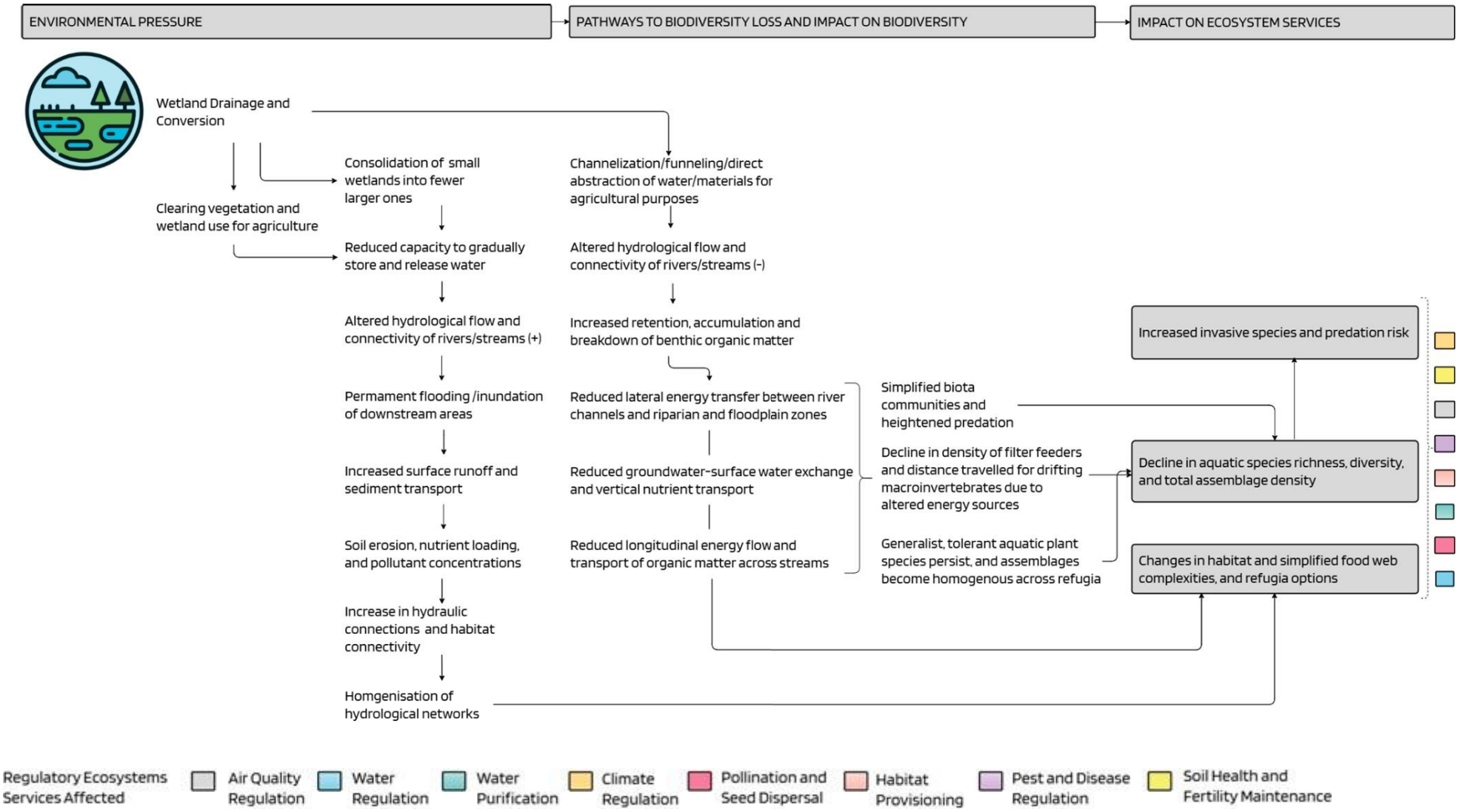


Figure 10 *- An illustration of the impact of wetland drainage on riparian and aquatic ecosystems.*

Source: Tosin Somorin/IWMI

3.3.2. Undue reliance on constructed storage and poor management of reservoirs

Over the past 50 years, global water demand has increased by approximately 1% per year, driven by population growth and economic development. The surge in demand has led to a considerable decline in freshwater storage and undue reliance on constructed storage systems. Over the last century, many human-built infrastructure works, such as dams, dykes, reservoirs, and irrigation canals, have been constructed for purposes including irrigation, flood control, hydroelectric power generation, and water supply. Among these, dams and reservoirs[6] account for most of the human-engineered storage solutions. Globally, there are 58,700 large dams, defined as those over 15 meters high or with a storage capacity of 3 million cubic meters. These dams store more than 16% of the annual river discharge of 40,000 cubic kilometers (Perera et al., 2021). There are also millions of smaller dams and reservoirs operating worldwide with diverse functions. In Asia and Africa, irrigation is the primary purpose of dams and reservoirs, whereas flood control, hydroelectricity, and water supply are more common in North America, Oceania, and Europe (Figure 11). Storage structures provide essential services, such as supporting irrigation on over 30% of irrigated land, which accounts for 40% of global agricultural production (ICOLD WRD, 2020). However, their construction and operation can have significant environmental and ecological implications. There is evidence that the construction of dams and storage facilities has had significant impacts on river and riparian ecosystems. It is estimated that 48% of global rivers have been altered by 6374 large dams (Grill et al., 2015; Schmutz et al., 2018). The manipulation of irrigation flows has caused extensive changes in river basins, affecting the natural features of watersheds (Ketchum et al., 2023). Only 37% of rivers over 1,000 kilometers remain free-flowing throughout their entire length, and just 23% flow uninterrupted to the ocean (Grill et al., 2019; GWP & IWMI, 2021). If the current trends persist and all proposed and under-construction dams are completed by 2030, it is estimated that natural river flow will be altered by 93% (Grill et al., 2015. Boxes 7 and 8 discuss the impact of impounding and altered flows on BESs.

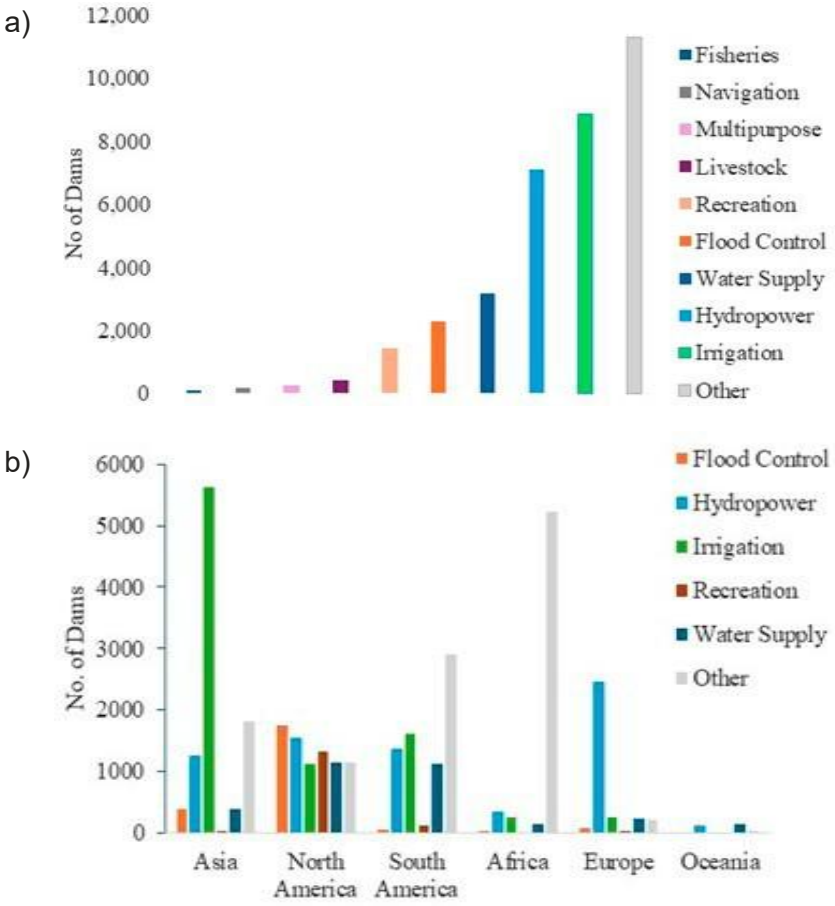


***Figure 11** − a) Distribution of Dams by function and b) number of dams along the major river basins of Asia, North America, South America, Africa, Europe, and Oceania (ICOLD WRD, 2020; Zhang & Gu, 2023).*

[6] Given there is no generally accepted definition for dams and reservoirs, in this chapter, "dams" refer to the physical structures, such as weirs, while the term "reservoir" is used to indicate the artificially created water body.

Box 7: Impact of impounding and water storage on flow regimes

Alteration of flow regimes is the most common consequence of inadequate design and construction, and inadequate control of storage structures. Both large and small storage structures reduce the lateral and vertical connectivity of rivers with their floodplains and wetlands (Rolls and Bonds, 2017). Dams, in particular, have fragmented over 60% of the world's rivers (Grill et al., 2019). They obstruct the natural flow of rivers, altering and redistributing available freshwater resources and limiting the amount of usable water that reaches the basin outlet. This further leads to the loss of natural storage, alters the physicochemical characteristics of reservoirs, and disrupts biological responses. The storage and capture of floodwaters can increase constancy and reduce flow variability, altering flooding regimes and affecting ecological processes. The storage and use of water for dry-season irrigation can increase downstream discharge from dams during the low-flow season, thereby causing cold-water pollution. Such impacts have been observed in rivers, such as the Indus in India, the Colorado in the USA, and the Murray-Darling in Australia (Grill et al., 2019). Figure 12 shows that globally, approximately 50% of rivers exhibit reduced connectivity, with a connectivity status index[7] (CSI) of less than 100%. The river connectivity index shows the lowest river connectivity in Europe, the United States, South Africa, China, and India. In the Flinders and Gilbert catchment in Australia, dam construction has reduced the average duration of lateral connectivity between floodplain wetlands and the main river by 1% and 2%, respectively. In the Atreyee River in India, the Mohanpur dam reduced lateral connectivity, resulting in a 66% decrease in floodplain wetlands. Furthermore, the vertical connectivity of these rivers is adversely affected by the regulated release of reservoir water, which alters nutrient, heat, and sediment exchange between surface and subsurface waters (Chen et al., 2023; Rolls and Bonds, 2017). Ultimately, the quantity, timing, and quality of environmental flows required to sustain freshwater ecosystems are affected.

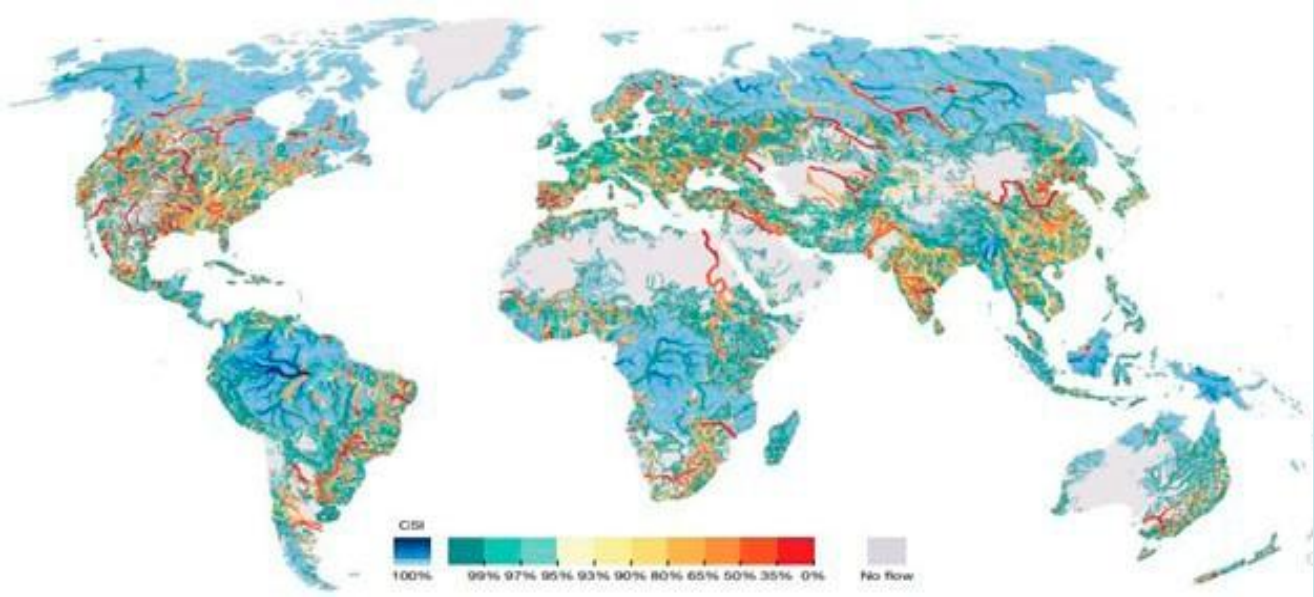


Figure 12 *− Global River connectivity status at the river scale based on the connectivity status index (Grill et al., 2019). Note: the blue shade indicates the magnitude of the river discharge, and the darker blue shade indicates the discharge of high magnitude from larger rivers.*

Reservoir operation also significantly affects various aspects (Figure 12), including variations in stored water, water-level changes, sediment capture and release, and downstream flow patterns. The magnitude of impact is influenced by the dam's location, reservoir size, water residence time, and time of application (dry versus wet periods) (Schmutz et al., 2018). Although the distinctive flow components within any given river will vary with geography and climate, common impacts associated with river damming and reservoir operation include the interruption of river continuity, which impedes longitudinal and lateral fish migration, sediment, and nutrient transport; sedimentation and siltation, which can clog riverbeds and degrade water quality; homogenization of habitats due to loss of lotic environments and the creation of lentic (still water) conditions; alteration of river/groundwater exchange leading to downstream riverbed incision and flow and quality changes (Tundu et al., 2018; Díaz-Redondo et al., 2018; Schmutz et al., 2018; Wang et al. 2022;). These impacts are brought about by several pressure-stress relationships and impact mechanisms: dams disconnecting reservoirs from floodplains, and reservoirs trapping sediments and nutrients, as well as thermal/chemical stratification leading to altered reservoir characteristics.

7 A CSI of less than 95% indicates a significant loss of connectivity in rivers either laterally or vertically

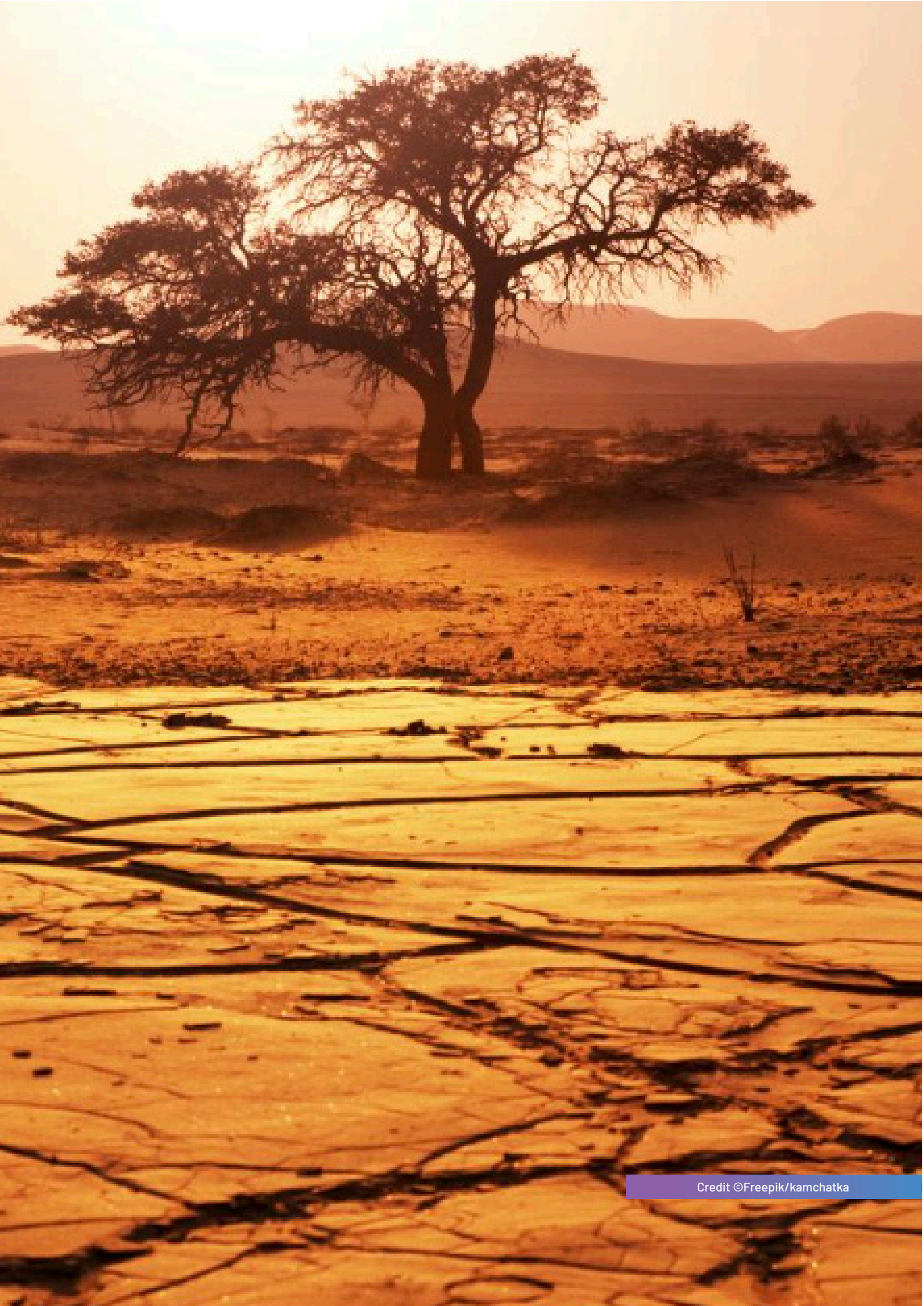
Box 8: Impact of altered flow variability on aquatic biodiversity

Watershed connectivity is critical to the biodiversity and ecosystem health of aquatic organisms, but dams and reservoirs can sever essential connections by prolonging low baseflows, reducing dam discharge, increasing flow variability, and reducing natural flow regimes (Rolls et al., 2012). This can disproportionately affect water habitats with steep gradients and ecosystems with fast-moving water, such as riffles and perennial rivers. The resulting changes in area, depth, and velocity can cause adverse impacts on the biodiversity of organisms like the foothill yellow-legged frog that are adapted to specific water flow, temperature, and quality conditions (Rolls and Bonds, 2017), affecting the composition of biota, trophic structure, and carrying capacity of habitats (Rolls et al., 2012). Low flows and shifts towards more intermittent flow patterns mediate changes in habitat conditions and degrade water quality. This, in turn, reduces biodiversity, disrupting the natural functions of critical aquatic systems and affecting population size, species richness, and species diversity (Datry et al., 2018). For example, non-migratory species adapted to stable environments tend to dominate in reservoirs, while migratory and rheophilic species are displaced. Dams and weirs transform flowing habitats into still-water habitats, reducing fish diversity within dams and slowing decomposition in streams. During periods of low flow, there may be a higher concentration of organisms, leading to competition for resources. Low baseflows can also affect plant communities, contributing to the spread of riparian plant species and altering overall population and species diversity in the area (Rolls and Bonds, 2017).

Alterations in flood magnitude and frequency resulting from flow regulation have been widely reported to affect ecosystems, including reduced abundance and richness of certain aquatic species. Reduced flow variability in regulated rivers has been linked to a decline in native fish species, a loss of riffle-dwelling taxa, and lower species richness of macroinvertebrates, periphyton, and macrophytes (Rolls and Bonds, 2017; Yamanaka Yamanaka et al., 2020). Additionally, reduced flow variability promotes the invasion of non-native species and affects the richness of terrestrial vegetation (Rolls et al., 2012; Hayes et al., 2017). In lowland rivers and estuaries, reduced flood magnitude and frequency can reduce ecological productivity, particularly in estuarine fisheries. Both the magnitude and seasonal timing of flooding strongly determine ecosystem productivity, and alterations to floodplain inundation dynamics by flow regulation could influence primary production in lowland river ecosystems. Studies in Australia and Portugal have shown that artificial perennial flow can cause significant shifts in fish assemblage composition and increase the abundance of broad-tolerance and nonnative taxa. In dryland rivers of Australia, changes from intermittent to permanent flow regimes have substantially altered biotic communities (Rolls and Bonds, 2017). Artificial flow permanence can also increase biofilm metabolic activity, chlorophyll productivity, and macroinvertebrate density and biomass (Ponsatí et al., 2014). This next section discusses how water impoundment and storage affect nutrient and material movement and the negative consequences of these processes for BESs.

Damming cold-water streams may also result in a potamalization effect, a shift from rhithral to potamal communities (Schmutz et al., 2018) due to favorable warmer temperatures. Here, low flows affect the sources and exchange of material and energy in riverine ecosystems (Rolls et al., 2012). Selective removal and transport of unnatural or unseasonal cold or warm water from large, stratified reservoirs can elicit ecological responses to flow-regime change. Sediment trapping occurs, often cumulative and preferential, in reservoirs. For example, coarse sediments tend to settle in the riverine section of the reservoir, while fine sediments and organic matter are deposited in the lacustrine zone. This affects downstream nutrient transport, reducing nutrient concentrations in coastal areas and degrading aquatic life and ecosystems. Over time, thermal/chemical stratification intensifies, leading to eutrophication. Depending on reservoir characteristics, layers of anoxic water or sediment may form due to stratification, deposition, and the decomposition of organic material. When conditions are regulated, habitat stratification can be more pronounced due to reduced turbulence, thereby affecting vertical mixing in the water column. None of these conditions operates in isolation, and many of the ecological pathways that are affected by low flows are likely to overlap or occur simultaneously, potentially resulting in synergistic and complex effects. Ultimately, these impacts result in habitat loss and fragmentation, disrupting life cycles, including breeding, feeding, and migration. They also interfere with the ecological functions of water, such as serving as a pathway for connectivity and the transport of materials and organisms in freshwater ecosystems (Rolls and Bonds, 2017; Barbarossa et al., 2020; World Bank, 2023; Grill et al., 2019; Sor et al., 2023; Chen et al., 2023).

Photo credit: Freepik/EyeEm



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3.4. Climate Change

Water is the primary medium through which the impacts of climate change are felt (Sadoff and Muller, 2009). As global temperatures rise, oceans warm and glaciers melt, significantly altering the availability, distribution, and quality of water resources. Climate change exacerbates the disruption of landscape linkages and amplifies ecological and biological responses through a complex set of natural processes and anthropogenic factors (Grimm et al., 2013; Macinnis-Ng et al., 2021; Weiskopf et al., 2020). This report provides a high-level description of climate impacts and drivers in relation to agricultural water management (Figure 13), relying on evidence synthesis reports to highlight the interconnections between climate change and anthropogenic activities. We have attempted to delineate climate drivers and impacts; however, these interactions are complex, involving multiple stressors, events, and feedback mechanisms. Boxes 9–15 highlight how climate change intensifies hydrological extremes: depleting and degrading groundwater, worsening drought and flooding risks, warming freshwater systems, and accelerating biodiversity loss; in turn, how agricultural practices amplify greenhouse gas emissions and ecosystem stress.

Box 9: Climate change impacts groundwater storage and quality

Studies by Condon et al. (2020) emphasize the crucial role of groundwater in buffering ecosystems against climate change and the risk of significant depletion as temperatures rise. Under climate change-induced conditions, warmer temperatures lead to higher evaporation rates in water bodies and soils. Groundwater quality and quantity, which are inextricably linked, are also affected (Dao et al., 2024). Warming indirectly affects groundwater storage by increasing evapotranspiration rates and shifting the balance between water supply and demand; however, the magnitude of the increase varies with regional water availability (Condon et al., 2020). Climate change also alters precipitation patterns and the distribution and quality of water across locations and timescales (Swain et al., 2022; Condon et al., 2020; do Nascimento et al., 2024). These effects are amplified in regions with extensive irrigation systems, such as the Alqueva Irrigation System in Southern Portugal, where climate change has led to a historical reduction in rainfall, thereby reducing surface runoff and groundwater recharge. The effects on water quality were particularly noticeable in the Gabros de Beja aquifer system (do Nascimento et al., 2024). Another notable impact was the significant increase in groundwater salinity, driven by processes that concentrated salts as regional water availability declined. Although nitrate levels in groundwater decreased, possibly due to changes in crop types and reduced fertilizer use, the concurrent rise in salinity posed a significant challenge. Salinization was linked to both natural geogenic processes and increased irrigation water use from surface sources, such as the Alqueva reservoir, which amplified evaporation. Monitoring groundwater also revealed associations between chloride and nitrate levels and climate factors, such as precipitation and evapotranspiration, suggesting that climate change affects the pathways and concentrations of these pollutants. For example, nitrate levels decreased due to dilution and changes in agricultural practices, whereas chloride levels were strongly linked to evapotranspiration patterns.

Box 10: Climate change exacerbates drought risks

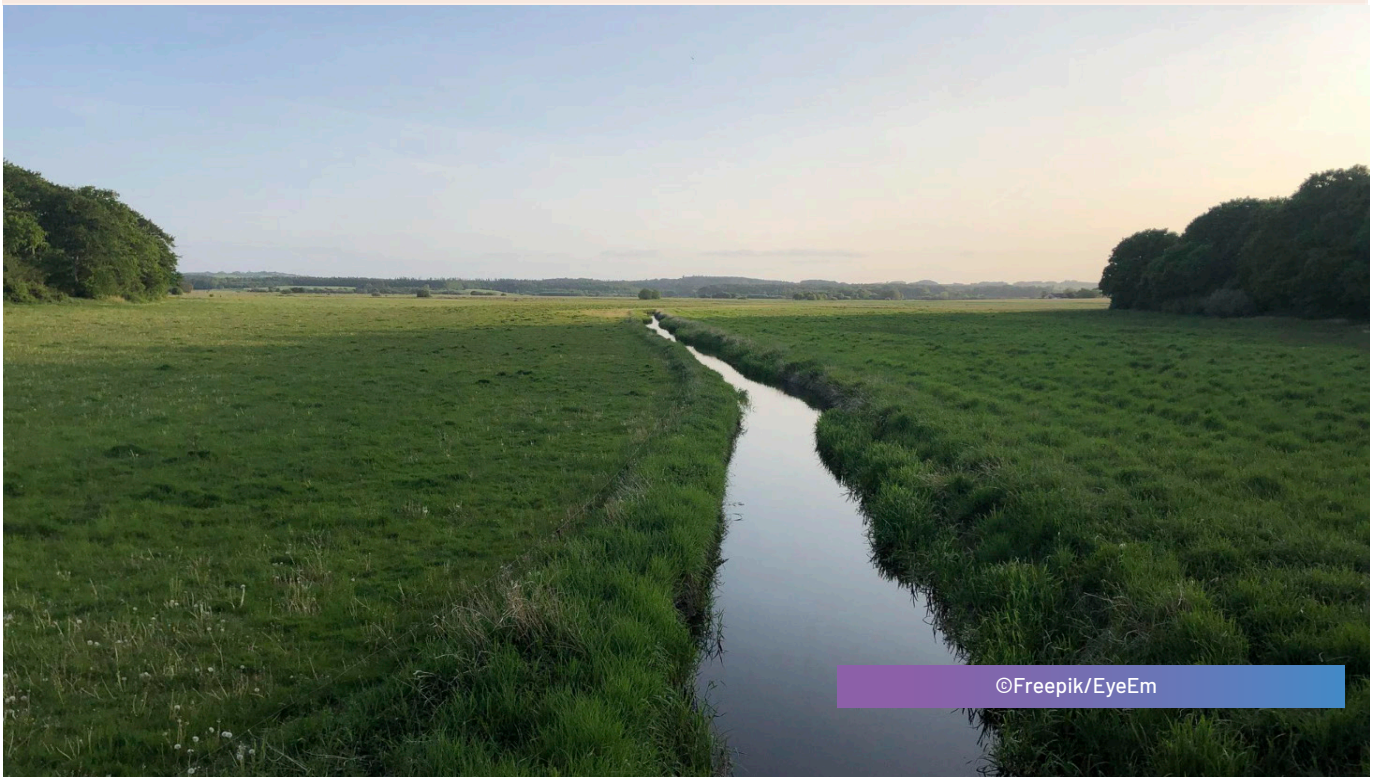
The global increase in extreme drought due to climate change is expected to result in more frequent and severe droughts across the Americas, Europe, Asia, and Africa (IPCC, 2022; Rosa, 2022). Droughts are typically categorized into four types: meteorological, hydrological, agricultural, and socio-economic (Zheng et al., 2023). Meteorological drought is caused by low precipitation, but, combined with increased evapotranspiration over several months to years, can lead to soil moisture drought and loss of vegetative cover. Agricultural drought occurs when soil moisture is below the threshold required for average crop growth and development, and it is prevalent in the root zone and topsoil (Pan et al., 2024). It can adversely affect water availability and quality when combined with hydrological drought (reduced water levels in rivers, lakes, and aquifers due to changes in ambient and surface conditions, such as precipitation and evapotranspiration rates). All the various forms of meteorological, hydrological, and agricultural droughts are predicted to increase in severity, duration, and frequency in several regions across the globe, including the upper Yangtze River basin, the Godavari River basin, and the Lower Mekong River basin (Sam et al. 2019; Feng et al., 2022; Khadka et al. 2024). Drought impacts are evident in Southern Europe and West Africa, where meteorological droughts (characterized by significantly reduced rainfall and declining soil moisture) have become more frequent (Dibi-Anoh et al., 2023; Ayugi et al., 2022; An et al., 2023). In these regions, drought is exacerbated by unsustainable water extraction for irrigation, which worsens conditions over time and prolongs local heat waves and dry periods. Severe droughts are particularly prevalent in arid and semi-arid regions and have adversely shifted and limited the timing of water availability on already stressed water systems (Bahir et al., 2020). It has a restricted water supply and inherently limits the geographical distribution of water in streams, rivers, and aquifers (Patel & Patel, 2024). It is changing agricultural water management practices, including irrigation methods, crop choice, and rotation. As a result, the area under irrigation has increased in many regions of the world, particularly in Africa and Asia, and changes in precipitation and temperature have rendered rainfed agriculture unprofitable (Holleman et al., 2020; Yamauchi, 2014; Alejo & Alejandro, 2022).

Box 11: Climate change exacerbates flooding risks

Climate also intensifies flooding events, though this is a natural part of the water cycle and is caused by meteorological processes. With global warming, the hydrological cycle is expected to intensify, increasing the frequency and intensity of extreme precipitation. This intensification increases flood risk in regions with greater water availability. Research by Tabari (2020) indicates that flood severity is closely linked to heavy rainfall, particularly in regions with abundant water resources. In areas with high humidity, flood intensity increases by 5.07% per 1 °C rise in temperature. Similarly, semi-humid and semi-arid regions experienced increases of 3.63% and 3.12%, respectively. However, dry areas demonstrate a slower response in flood intensity due to reduced soil moisture and higher evaporation rates. Furthermore, seasonal changes in water availability significantly affect the risk of flooding. During wetter seasons, such as winter, extreme precipitation and flood intensity increase more strongly, with flood intensity rising by 9.53% for each degree of warming. This seasonal variation suggests that flood risk is elevated during periods of higher moisture. Climate change exacerbates flooding by increasing the frequency and intensity of extreme weather events, for example, by producing more intense and prolonged rainfall, overwhelming rivers, lakes, and drainage systems, and causing fluvial flooding. The accelerated melting of snow and ice contributes to higher river flows and sea levels. In agricultural systems, intense rainfall that exceeds drainage capacity can exacerbate pluvial and fluvial flooding, leading to nutrient and pollutant runoff into rivers and oceans and to flow that backs up and overflows onto land. The intensity of impacts will depend on existing biophysical conditions, e.g., soil moisture, vegetation cover, and catchment characteristics (Rupngam and Messiga, 2024).

Box 12: Impact of surface/groundwater warming degrees

Climate change is increasing surface/groundwater temperatures, which can significantly impact water quality and freshwater ecosystems. Thermal stratification occurs in large lakes and oceans, with warming occurring at a faster rate than in the surrounding air. This leads to shorter ice-cover periods, increased nutrient-rich waters, and reduced productivity in the world's major ocean basins (Grimm et al., 2013; Woolway et al., 2022; Piccolroaz et al., 2024). A time-series analysis by Riedel (2019) also found that soil and groundwater temperatures have been increasing at rates of 0.1–0.4 K per decade, leading to subtle yet distinct changes in groundwater pH and oxygen levels. Groundwater temperature changes can influence gas solubility, organism metabolism, and oxygen concentrations, leading to shifts in redox conditions and the mobilization of redox-sensitive constituents such as arsenic and phosphorus (Benz et al., 2024). Surface water temperatures are influenced by atmospheric heat fluxes, but groundwater discharge can decouple this by raising ambient water temperatures (Johnson et al., 2020). These changes can trigger hypoxic or anoxic conditions and alter microbial community composition, leading to shifts in reproductive cycles, food-web links, and loss of sensitive species (Benz et al., 2024).



Box 13: Impact of climate change on biodiversity loss

Climate change can profoundly affect species composition, ecosystem functioning, and the overall health of freshwater ecosystems. Freshwater and related ecosystems are especially vulnerable to climate change because they are physically fragmented and heavily exploited by humans for various purposes. Many species in these habitats have limited abilities to disperse as the environment changes, water temperature and availability are climate-dependent, and these systems are exposed to numerous human-made stressors (Woodward et al., 2010; Pletterbauer et al., 2018). They cover less than 1 percent of the Earth's surface but host approximately one-third of vertebrate species and 10 percent of all species (Stayer and Dudgeon, 2010), including mammals, birds (IUCN, 2019), and fish (Fricke et al., 2020). These ecosystems are directly threatened by depletion of water quality and quantity, with warmer temperatures forcing many species to shift their ranges poleward or to higher altitudes (Weiskopf et al., 2020). It also leads to local extinctions, particularly for species unable to migrate or adapt quickly. There is some evidence that warmer conditions affect the metabolic rates and foraging behavior of fishes (e.g., ectotherms), accelerating life cycles, altering species interactions (e.g., predation and competition), and changing food-web structure (Gauzens et al., 2024). These shifts can disrupt ecosystem balance, leading to reduced species diversity and changes in community structure.

For example, increased temperatures can favor smaller, heat-tolerant species, altering food webs and reducing overall biodiversity and ecosystem resilience. Long-term monitoring of Wolf Point Creek in Northeastern Montana showed that stream ecosystems change significantly with temperature (Flory et al., 2000). Warmer conditions led to increased taxon richness, but some species were lost. Colonization was largely temperature-dependent up to approximately 10°C, but beyond this threshold, community development and ecosystem effects were unpredictable due to the influence of other stressors, such as pollutant concentrations (Woodward et al., 2010). The magnitude of impacts will vary for the different levels of organizations, and response rate to climate change-induced stressors may vary due to factors such as thermal threshold, habitat alteration, resource availability, competition with invasive species, and predator-prey dynamics (Weiskopf et al., 2020; Woodward et al., 2010). Shifts are likely to be rapid and erratic, leading to nonlinear community responses. At the individual level, basal metabolic rate, which is linked to body size and temperature, is important. As temperatures rise, metabolic rates increase, changing species interactions and ecosystem dynamics. At the population/ community level, species that cannot tolerate heat may shift their ranges poleward or to higher elevations as temperatures increase. This can lead to local extinctions and invasions by more heat-tolerant species.

Warming temperatures can alter species interactions, such as predation and competition, thereby altering community structure and function. At the ecosystem level, warming temperatures can shift community size structure, with smaller organisms becoming more dominant (Woodward et al., 2010). All these impacts have significant implications for food web dynamics. Nutrient cycling, decomposition, and primary production are highly sensitive to temperature changes. For instance, warming can increase heterotrophy and reduce CO_2 sequestration, pushing ecosystems towards more turbid, plankton-dominated states. Indirect consequences may affect land-based vegetation, such as *Tamarix* spp., which can alter the hydrologic conditions of riparian soils and influence streamflow (Shafroth et al., 2005). The impacts can induce biome shifts in grasslands and tundra, enabling woody invasion of herb-dominated ecosystems and increasing shrub and grass-like plant cover (Zavaleta et al., 2006; Yu et al., 2022). This can affect the biodiversity of terrestrial ecosystems and the phenology of wetland species, thereby shifting plant species distributions and ecosystem performance.

Box 14: Impact of agricultural practices on climate change

Surface flooding due to poor scheduling or expanded irrigation increases the concentrations of potent greenhouse gas emissions, including CO_2, nitrous oxide (N_2O, and methane (CH_4. Several studies have investigated flooded paddy rice fields and reported significant CH_4 emissions from anaerobic decomposition and anoxic conditions in the root zone (Sander et al., 2014. The major pathways for methane production in flooded soils are the reduction of CO_2 and the transmethylation of acetic acid or methanol by methane-producing bacteria (IPCC, 1997. Methane is also released via diffusive transport through plants to the atmosphere, but it can also bubble from the soil and across the water surface during land preparation and early plant growth. At the same time, methane flux in paddy rice fields varies geographically and temporally, depending on soil type, texture, nutrient composition, and agricultural practices. Production peaks when soil redox potential drops below -150 mV after flooding (Islam et al., 2020. Emissions of nitrous oxides are a consequence of nitrogen inputs to soil and occur via a range of microbial transformation pathways, including nitrification, nitrifier-denitrification, and denitrification, but oxygen availability plays a key role (Elberling et al., 2023. Surface flooding reduces oxygen and nitrogen diffusion through soils. This creates anoxic conditions and reduces microbial growth and activity, particularly those associated with nutrient cycling, thereby intensifying chemical use on farms and increasing runoff of fertilisers and pesticides into water bodies (Furtak and Wolińska, 2023).Excessive irrigation water use worsens climate change by rapidly depleting water sources, disrupting natural hydrological cycles, and causing shifts in habitats and biomes (Russo and Lall, 2017; Rajan et al., 2020; Balasubramanya et al., 2024. Additionally, pumping water for irrigation contributes to climate change as it requires significant energy, often derived from fossil fuels. Other agricultural activities and landscape alterations, including wetland drainage, peat extraction, and intensive use of mineral fertilisers, can also release stored carbon, further contributing to local and regional climate change. For instance, the use of nitrogen-based fertilizers on irrigated farmland is a primary source of nitrate emissions into water and nitrous and nitric oxide emissions into the atmosphere (Liu et al., 2024. The resulting decomposition of organic matter, a consequence of soil and water pollution, also increases carbon emissions. In wetland and coastal ecosystems, the influx of saltwater accelerates decomposition, including peat decomposition. This reduces these soils' capacity to store carbon and ultimately contributes to higher atmospheric greenhouse gas concentrations (Herbert et al., 2015. As peat is lost and the land sinks, it also facilitates the movement of saltwater inland and degrades the affected land.

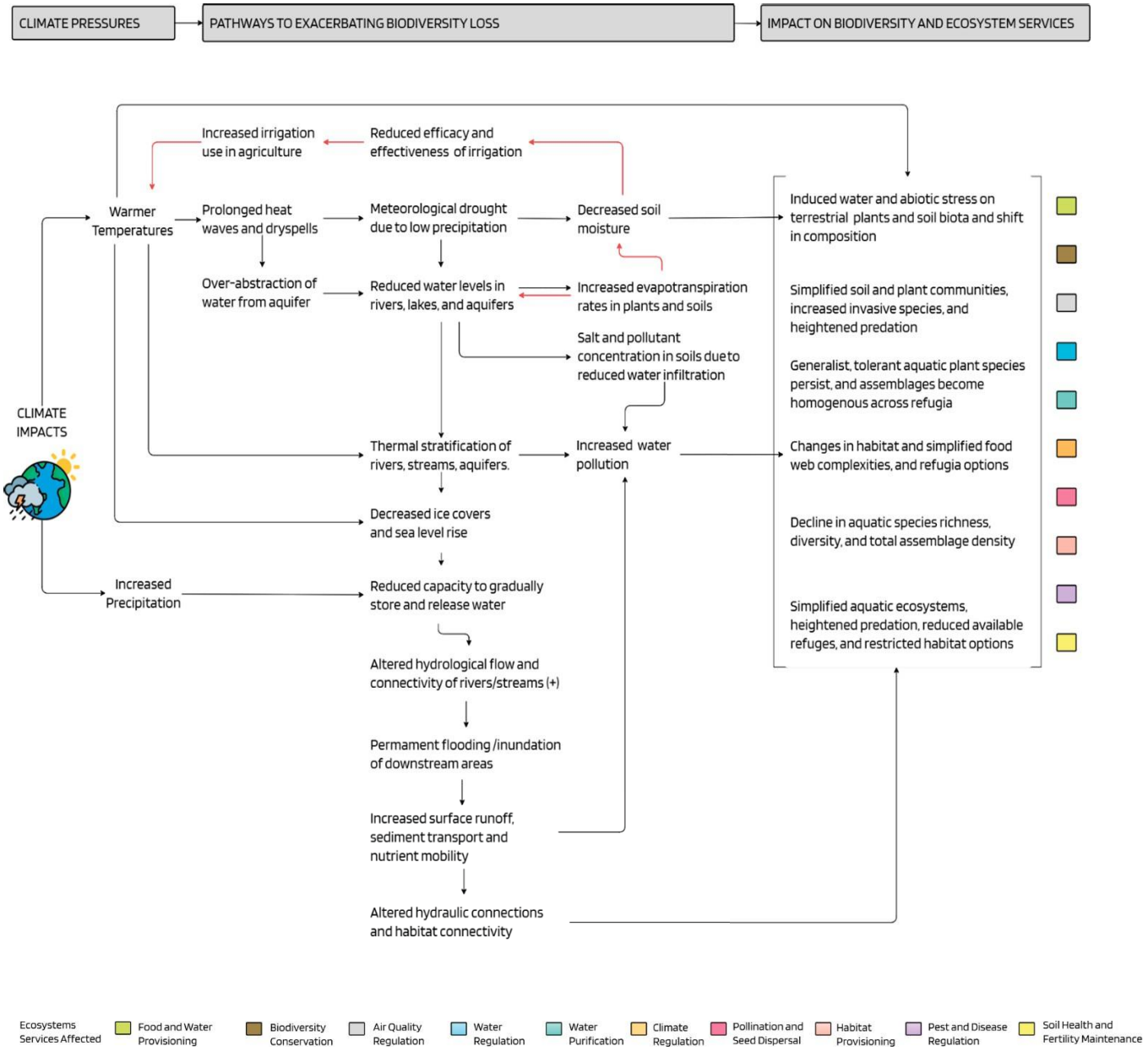


Figure 13 - An illustration of how climate change aggravates pesticide use and biodiversity loss.

Source: Tosin Somorin/IWMI

4. CONCLUSION

This report shows that agricultural water management sits at the heart of the accelerating crisis of biodiversity loss. The evidence clearly demonstrates that water-related decisions, including how much is extracted, how it is stored, how it flows across landscapes, and how polluted it becomes, shape ecological outcomes as profoundly as land-use change or chemical inputs. This study has shown that poor irrigation practices intensify soil degradation through salinization, waterlogging, and nutrient depletion, eroding below-ground biodiversity and weakening the productive capacity of farms. Excessive withdrawals from rivers and aquifers disrupt environmental flows and fragment aquatic habitats, adversely affecting freshwater species.

Equally concerning is the way polluted return flows transform freshwater ecosystems. Runoff enriched with fertilizers, pesticides, and sediments simplifies food webs, favors a small number of tolerant species, and diminishes ecosystem functions such as nutrient cycling and water purification. These ecological shifts undermine agricultural resilience by increasing pest exposure, reducing water availability, and compromising soil and crop health. Irrigation canals and engineered water systems, meanwhile, reshape entire landscapes by facilitating the spread of invasive species and reducing habitat connectivity across farms, wetlands, and riparian zones.

The agricultural-driven pressures documented in this report illustrate the urgent need to reposition agricultural water management not only as a productivity agenda but as a biodiversity and ecosystem services agenda. Sustainable water allocation, improved irrigation efficiency, watershed protection, and integrated landscape governance offer pathways to balance production with nature. This requires integrating biodiversity into water allocation decisions, strengthening watershed protection, and aligning agricultural incentives with ecological outcomes. Without such measures, water-related degradation will continue to erode the natural capital on which agriculture ultimately depends. Strengthening institutions, investing in monitoring systems, and enabling cross-sector coordination will be essential to transition toward water management approaches that protect both livelihoods and ecosystems.

To achieve nature-positive outcomes, interventions should prioritize the restoration of hydrological and ecological functions alongside agricultural productivity. Key actions include incentivizing the adoption of efficient irrigation technologies, protecting environmental flows, and rehabilitating wetlands and riparian buffers to restore habitat connectivity. Farmers should be supported in adopting soil- and water-conserving practices and nature-based solutions. Embedding circular economy principles in these efforts is essential: water must be valued as a finite resource; agricultural runoff and wastewater should be minimized and safely reused; and organic residues should be transformed into inputs that enhance soil health. Such interventions can regenerate landscapes, support the recovery of ecosystem functions, and sustain water-dependent biodiversity. Importantly, the insights from this report can inform policy and investment strategies to reduce the key stressors driving biodiversity loss. By identifying where water mismanagement creates the greatest ecological risks, decision-makers can target resources toward high-impact interventions, strengthen regulatory frameworks, and design financing instruments that reward sustainable water use, pollution reduction, and watershed restoration. This ensures that future agricultural development aligns with long-term ecological resilience.

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