Int. j. adv. multidisc. res. stud. 2025; 5(6):659-668

Received: 25-09-2025
Accepted: 05-11-2025

International Journal of Advanced Multidisciplinary Research and Studies

ISSN: 2583-049X

Research and Assessment of Salinity Intrusion Trends in the Lower Ma River Under the Context of Climate Change

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DOI: https://doi.org/10.62225/2583049X.2025.5.6.5254
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Abstract
The coastal plain of the Ma River has a 102km long coastline, including the districts: Nga Son, Hau Loc, Hoang Hoa, Sam Son City, Quang Xuong, Tinh Gia with estuaries: Cua Hoi, Lach Sung, Lach Truong, Lach Hoang. This is a densely populated area that is considered to have a high economic development rate according to the trend of economic restructuring and crop structure transformation, so the demand for water resources is increasing. In recent years, the lower reaches of the Ma River have been heavily affected by salt intrusion, especially in the context of climate change, the level of impact is more serious. In the dry season, when the water level at the downstream stations is much lower than the multi-year average, the amount of flow from upstream drops sharply, creating an opportunity for salt to go deeper into the inland, causing considerable damage in agricultural production, aquaculture and seafood in coastal areas.

Keywords: Saltwater Intrusion, Climate Change, MIKE 11, Hydrodynamic Modeling, Ma River Basin, Salinity Hazard Mapping, Water Management

Introduction

Saltwater intrusion has emerged as a critical hydrological and environmental concern in many coastal and estuarine regions worldwide. With increasing anthropogenic pressures, intensified droughts, and accelerated sea-level rise due to global climate change, the interactions between freshwater discharge and tidal dynamics are becoming more complex and more extreme. River basins with strong seasonality, particularly monsoon-dominated systems in Southeast Asia, are highly vulnerable to saltwater intrusion during extended dry seasons when upstream flow is markedly reduced. The increasing severity of saline intrusion impacts agricultural productivity, drinking water supply, industrial development, and ecosystem health, ultimately threatening socio-economic stability in coastal areas.

In Vietnam, a country with over 3,260 km of coastline, saltwater intrusion is a recurrent and increasingly severe challenge. While the Mekong Delta is the most widely studied case, significant impacts have also been reported in northern coastal provinces—including Thai Binh, Nam Dinh, Ninh Binh, and Thanh Hoa. Among these, the Ma River Basin is one of the largest in the region, spanning multiple provinces and serving as the primary freshwater source for irrigation, domestic use, and industrial operations in Thanh Hoa Province. The lower Ma River supports an extensive agricultural economy, with rice cultivation, aquaculture, and salt-making activities heavily dependent on controlled freshwater availability during the dry season.

The downstream area of the Ma River is characterized by a dense system of irrigation canals, pumping stations, and sluice gates distributed across districts such as Nga Son, Hau Loc, Hoang Hoa, Sam Son, Quang Xuong, and Tinh Gia. These areas regularly experience saline intrusion during the dry months, particularly from February to May, when upstream runoff is insufficient to counterbalance tidal forcing from the East Sea. In recent decades, the frequency and severity of saline intrusion events have increased significantly, coinciding with years of strong El Niño activity and prolonged drought. This trend has resulted in reduced irrigation water availability, crop stress, decreased drinking water quality, and increased economic losses for local communities.

Despite the growing importance of this issue, research on the Ma River Basin has remained limited compared to southern river systems. Existing studies have primarily focused on hydrological characteristics, water quality monitoring, or isolated modeling efforts. Few studies have systematically evaluated the spatiotemporal patterns of saltwater intrusion under future climate-change conditions, particularly using integrated model frameworks capable of capturing the complex interactions between hydrology, hydrodynamics, and salinity transport. Furthermore, there remains a lack of hazard mapping at the commune level, which is essential for supporting local authorities in designing targeted adaptation and water-management strategies.

The MIKE modeling suite developed by the Danish Hydraulic Institute (DHI) has been widely applied worldwide for hydrological and hydrodynamic simulations, including salinity intrusion studies. The MIKE NAM rainfall–runoff model effectively captures basin-scale hydrological responses to climate variability. The MIKE 11-HD module provides robust simulation of water levels and discharge in river networks, while MIKE 11-AD enables detailed analysis of salinity transport driven by advection–dispersion processes. Integrating these three modules provides a powerful approach for analyzing saltwater intrusion dynamics across seasonal and climatic time scales.

In this study, an integrated MIKE NAM–MIKE 11-HD–MIKE 11-AD modeling system is developed for the lower Ma River Basin. The model is calibrated and validated using observed hydrometeorological and salinity data covering the period 2009–2016, including both normal and severe-drought conditions. Climate-change projections for 2030 and 2050 are incorporated to assess future changes in salinity intrusion under different low-flow scenarios, reflecting seasonal variability and potential long-term hydrological shifts.

Introduction: The Global Environmental Crisis in Context

Human activities have triggered a profound global environmental crisis marked by interlinked challenges in climate, biodiversity, land, and pollution. As one recent analysis notes, humanity now faces "an era of converging crises: climate change, ecological destruction, disease, pollution, and socioeconomic inequality". These pressures manifest as record-breaking warming of air and oceans, accelerating species declines, widespread habitat loss, expanding deserts, contaminated air and water, and accumulating waste. Scientists increasingly describe our epoch as the **Anthropocene**, a term coined by atmospheric chemist Paul Crutzen to capture the idea that human influence has become a dominant geological force on Earth. In the Anthropocene, population growth, intensive industry, and high consumption have altered biogeochemical cycles, land cover, and the climate system so substantially that many researchers argue we have entered a new geological epoch in Earth's history. This view calls for a holistic perspective on human–nature interactions, recognizing both the harms and the potential for sustainable stewardship.

Complementing the Anthropocene concept is the **planetary boundaries** framework, introduced by Rockström *et al.* (2009) and updated subsequently. This framework attempts to define a "safe operating space" for humanity by identifying critical Earth-system thresholds. It specifies nine boundaries – including climate change, biosphere integrity (biodiversity loss), land-system change, freshwater use, biogeochemical flows (nitrogen and phosphorus cycles), ocean acidification, atmospheric aerosol loading, stratospheric ozone depletion, and novel entities (e.g. plastics) – beyond which human actions risk destabilizing the Earth system. The planetary boundaries model emphasizes that crossing these limits could trigger "rapid, non-linear and irreversible changes". In other words, humanity's survival and prosperity rely on keeping global processes within safe limits. Together, the Anthropocene and planetary boundaries concepts underscore that the current environmental crisis is global, systemic, and unprecedented. They highlight an urgent imperative: the need to recognize planetary-scale change and to steer human development back within sustainable limits.

This review examines the major facets of the global environmental crisis in detail. We first discuss the science, causes, impacts, and mitigation of **climate change**, the most pervasive Earth-system change. We then turn to **biodiversity loss**, analyzing the drivers of species decline and conservation responses. **Pollution** is treated next, covering air, water, soil, and plastic pollution and their effects on health and ecosystems. We follow with **deforestation and land degradation**, exploring why forests and soils are being lost and how restoration can help. We then address **freshwater and ocean challenges**, from water scarcity on land to acidification, overfishing, and marine pollution in the seas. Finally, we review **governance and solutions** – the policies, treaties, and sustainability models intended to address these crises. Throughout, we integrate the latest scientific data and examples. By presenting each section in turn, this article provides a comprehensive, up-to-date overview of global environmental issues and the frameworks proposed to understand and solve them.

Climate Change: Science, Impacts, and Mitigation

The Scientific Basis and Human Causes

The science of climate change is well established: the atmospheric concentration of heat-trapping greenhouse gases (GHGs) has risen dramatically due to human activities, altering Earth's energy balance. Since the Industrial Revolution, carbon dioxide (CO_2) levels have surged from about 278 parts per million (ppm) to roughly 420 ppm today, a rise of over 50%. Other anthropogenic GHGs – notably methane (CH_4) and nitrous oxide – have also increased. These gases trap infrared radiation that would otherwise escape to space, warming the planet. Observational and modeling studies attribute virtually all of the observed warming over the past century to human emissions. Indeed, NASA scientists confirm that the recent global warming trend is driven by these greenhouse gases. As one summary states, "Scientists have concluded that the warming trend is driven by rising carbon dioxide, methane and other greenhouse gases" emitted by fossil fuel use and land-clearing. In short, an overwhelming consensus holds that anthropogenic GHG emissions are the primary cause of modern climate change.

These emissions come mostly from burning coal, oil, and natural gas, as well as deforestation and agricultural practices. According to the Global Carbon Budget (2024), fossil-fuel combustion contributed a record ~37.4 billion tonnes of CO_2 in 2024, up 0.8% from 2023. Land-use change (chiefly deforestation) added another ~4.2 billion tonnes. In total, humans now emit over 40 billion tonnes of CO_2 each year, roughly ten times preindustrial levels. The steady growth of global emissions – with no clear sign of having peaked – means atmospheric CO_2 is climbing faster than ever. (The 2024 figure of ~422.5 ppm CO_2 is about 52% above 1750 levels.) Methane and nitrous oxide emissions, from agriculture, fossil fuels, and waste, further amplify warming. The physics is straightforward: more GHGs raise the planet's greenhouse effect, trapping extra heat and causing the climate system to warm.

Observed Warming and Impacts

The rise in GHGs has already produced significant and accelerating warming. The Earth's global mean surface temperature is now roughly 1.3–1.5°C higher than late 19th-century levels. In particular, NASA reports that 2024 was the warmest year on record: global temperature was 1.28°C above the 20th-century average and about 1.47°C above mid-19th-century values. Notably, for much of 2024 the world experienced more than 1.5°C of warming compared to pre-industrial times, which suggests we may have temporarily breached the Paris Accord's 1.5°C target. Indeed, climate data show a pattern of ever-increasing record highs. NASA notes that virtually all of the past decade has set successive temperature records, making the 2020s likely the hottest decade on record.

These temperature increases have myriad impacts. Even the 1.1°C of warming that has already occurred (as of the early 2020s) has produced changes "unprecedented in recent human history". For example, sea levels have risen measurably due to thermal expansion of the oceans and melting of land ice. Arctic and Antarctic sea ice, as well as mountain glaciers, are shrinking dramatically. Heat waves have become more frequent and intense globally, while heavy precipitation and storm events have grown more extreme in many regions. The World Resources Institute (summarizing IPCC AR6 findings) reports that climate-related extremes now occur in every region – from droughts and wildfires to floods and cyclones – causing significant harm to ecosystems and human systems. A series of devastating heat waves in Europe, North America, and Asia during the 2020s, and the loss of coral reefs and alpine ecosystems, illustrate the broad scope of climate impacts. The latest science finds that every tenth of a degree of warming avoided reduces the risk of catastrophic outcomes, including tipping points like the collapse of the Greenland Ice Sheet, dieback of the Amazon rainforest, or mass mortality of key species. In short, even at the current ~1.3°C warming, the climate is already behaving in ways dangerous to societies and ecosystems, and the trajectory suggests much worse to come without intervention.

Urgency: Carbon Budgets and Thresholds

Because climate change is driven by the cumulative amount of CO_2 emitted, scientists have calculated remaining "carbon budgets" to limit warming to specific targets. A widely cited recent analysis finds that at current emission rates, there is only a slim chance of staying below 1.5°C. In fact, continuing "business as usual" emissions could consume the remaining 1.5°C budget within about six years. This means that to have a 50% probability of limiting warming to 1.5°C (with no or limited overshoot), global CO_2 emissions would need to decline very rapidly, reaching net zero by mid-century. Current national commitments – the climate pledges countries submitted under the Paris Agreement (NDCs) – fall far short of this. Recent gap reports conclude that if all announced targets are met, average warming this century will still reach about 2.3–2.5°C. For example, the UN Environment Programme's 2025 Emissions Gap Report notes that current pledges imply ~2.4°C by 2100, which is dangerously above the 1.5–2°C goals. Even with optimistic pledges, only about 14% of the necessary reductions for 1.5°C are currently achieved. In practical terms, this means that without much stronger action, the world is very likely to overshoot 1.5°C this century. The UNEP analysis warns that making up this gap will require "drastic" cuts (roughly 35–55% below 2019 levels by 2035, depending on the warming limit).

Mitigation and Solutions

Fortunately, science also offers a menu of mitigation strategies. The primary goal is to slash GHG emissions as rapidly as possible and eventually reach net-zero CO_2 (and large cuts in methane, etc.). This involves decarbonizing the global energy system: phasing out coal, oil, and natural gas in favor of renewable sources (solar, wind, hydro, geothermal), along with major improvements in energy efficiency. Investment in low-carbon infrastructure (grids, public transit, electric vehicles), as well as carbon capture and storage (CCS) technologies, can further reduce emissions. Numerous countries and companies have already announced long-term net-zero targets (e.g. 2050 or 2060 targets), covering much of the world economy. Rapid expansion of renewables is already underway: wind and solar capacity are growing exponentially, with renewables (including hydro) now supplying on the order of 30% of global electricity. This technological shift is helping bend the emissions curve in some places, but not yet fast enough.

On the policy front, international cooperation under the UNFCCC remains central. The Paris Agreement (2015) [30] commits nearly all nations to set increasingly ambitious emission targets and to review progress regularly. The latest "global stocktake" (in 2023) concluded that current policies and pledges are insufficient, echoing the gap reports' findings. Beyond national pledges, climate finance for developing countries and removal of fossil fuel subsidies are widely seen as necessary. Other governance strategies include carbon pricing mechanisms (taxes or cap-and-trade systems) which are in place in many jurisdictions, deforestation moratoria, and regulations on high-GWP pollutants.

To date, mitigation has also benefited from significant shifts: for instance, the cost of solar PV and wind power has plummeted, making clean energy increasingly competitive. Yet analyses stress that **far stronger** action is needed soon. If emissions continue at current rates, models show that even a 2°C warming pathway would require extremely aggressive cuts over the next decade. In summary, climate science clearly shows that (1) human GHG emissions are causing unprecedented warming, (2) this warming is already having serious impacts and portends worse if unchecked, and (3) rapid, large-scale mitigation – transforming energy, transport, industry, and land use – is urgently required to avert the worst outcomes.

Biodiversity Loss: Drivers, Consequences, and Conservation

Scope of the Crisis

Biodiversity worldwide is declining at an alarming rate. The latest assessments indicate massive losses of wildlife and habitat that threaten ecosystem function and human wellbeing. The WWF's *Living Planet Report* (2022) finds that monitored populations of mammals, birds, fish, reptiles and amphibians declined by an average of **69%** between 1970 and 2018. Likewise, the Intergovernmental Science-

Policy Platform on Biodiversity and Ecosystem Services (IPBES) reported in 2019 that up to **one million species** are currently threatened with extinction, rates tens to hundreds of times higher than the historical background rate. In practical terms, many iconic species have suffered: tropical rainforest species, ocean fishes, amphibians, and pollinators are all in steep decline. Even common species (e.g. birds and insects in many regions) have fallen sharply, raising concerns about "empty forest" and "empty field" phenomena. Biodiversity loss not only erodes the richness of life on Earth, it undermines nature's contributions to people – such as crop pollination, water purification, disease regulation, and climate stabilization – with direct impacts on food security, health, and economies.

Drivers of Biodiversity Loss

The primary drivers of biodiversity loss are well identified. Habitat destruction and modification loom largest. Agriculture (both large-scale and subsistence) is the biggest driver: clearing forests and converting wetlands to cropland or pasture decimates native ecosystems. For example, an analysis by the Intergovernmental Panel on Climate Change and others shows that agricultural expansion – notably cattle ranching, soybean cultivation, and oil palm plantations – accounted for about 40% of tropical deforestation between 2000–2010, with subsistence farming adding another ~33%. In total, roughly 420 million hectares of forest have been lost since 1990, mainly for farming and development. This large-scale land-use change destroys habitat outright and fragments the remainder, making survival of specialist species difficult. Even where forests remain standing, logging, road-building and urban sprawl fragment landscapes, isolating wildlife populations.

Other land and water uses also matter. Infrastructure (roads, dams, mines) disrupts ecosystems. Overfishing and destructive fishing gear (bottom trawling, blast fishing) degrade marine habitats. Unsustainable harvesting of timber, wildlife, and medicinal plants (including illegal poaching and trafficking) puts direct pressure on species. Pollution is another major threat: persistent pesticides, nutrient runoff, industrial chemicals and heavy metals have poisoned soils and waters, harming insects, fish and amphibians. In particular, plastic debris (discussed in the Pollution section below) is accumulating in both terrestrial and marine habitats, affecting hundreds of species (86% of marine turtles, 44% of seabirds, 43% of marine mammals have been found with plastic ingestion or entanglement). Climate change itself is an increasing driver: warming, extreme weather, and shifting precipitation patterns are altering habitats faster than many species can adapt. The IPBES report emphasizes that these drivers act in combination: e.g. clearing habitat can amplify climate impacts and vice versa. For instance, rising temperatures stress coral reefs already weakened by pollution and overfishing, causing mass bleaching. Invasive alien species introduced by trade or travel can further spread disturbance and compete with native life. In summary, the five most important drivers are widely cited as land-use change (habitat loss), overexploitation of wild species, pollution, invasive species, and climate change.

Consequences of Biodiversity Decline

The ecological consequences of these losses are profound. Ecosystems with reduced biodiversity function less effectively. For example, declines in pollinators and soil organisms can impair plant reproduction, reducing crop yields. Loss of predators can lead to pest outbreaks. Wetland destruction reduces natural water filtration, worsening water quality downstream. Biodiversity decline also weakens nature's resilience: simpler ecosystems have a harder time withstanding stresses like droughts or disease outbreaks. For humans, the losses translate into real risks: food systems become less stable, new zoonotic diseases may emerge as wildlife contacts increase, and cultural values tied to nature can vanish. Economically, nature-based industries (fisheries, forestry, ecotourism) suffer. In sum, the collapse of biodiversity is not just an abstract environmental issue – it directly undermines ecosystem services that billions of people rely on. The dire pace of loss has prompted dire warnings: scientists stress that the current biodiversity crisis "threatens human well-being as much as climate change", with some estimates suggesting that around half of global economic output is moderately or highly dependent on nature (through tourism, agriculture, etc.) and would be impacted by further degradation.

Conservation and Restoration Efforts

Addressing biodiversity loss requires a combination of protected area expansion, sustainable management, and restoration. Internationally, the Convention on Biological Diversity (CBD) provides a framework. In late 2022, CBD Parties agreed to the Kunming-Montreal Global Biodiversity Framework, including a target (the so-called "30×30" goal) to protect 30% of Earth's land and seas by 2030. As of 2024, about 17.6% of the world's land area and 8.4% of the oceans are formally protected, far below this goal. The first official assessment of Target 3 (30% by 2030) finds that protected areas must almost double on land and more than triple at sea to meet the commitment. Moreover, protection efforts must focus on the most biodiversity-rich areas: currently only about one-fifth of key ecological hotspots are fully protected.

Many countries have begun creating new parks and reserves, and in some cases recovered species. Approximately 51 nations have already achieved over 30% conservation coverage on land, demonstrating feasibility. Beyond protected areas, conservation efforts include sustainable fisheries management (quotas, no-take zones), anti-poaching patrols, wildlife corridors between fragments, and control of invasive species. Habitat restoration is gaining attention too: initiatives like the UN Decade on Ecosystem Restoration (2021-2030) encourage replanting of degraded forests and wetlands. Funding is crucial: the CBD framework calls for tripling biodiversity finance (to at least USD 200 billion per year) by 2030.

On the legislative side, countries enforce regulations such as the U.S. Endangered Species Act or the EU's Habitats Directive; globally, conventions like CITES regulate international trade in threatened species. Private efforts (e.g. corporate commitments to zero deforestation, community-managed reserves) also play roles. Nevertheless, current actions fall far short of needs. The protected area network, for instance, often lacks adequate management and fails to address ecosystem connectivity or community rights. Nevertheless, there are success stories (e.g. some recovered wildlife populations, new marine reserves) indicating that concerted efforts can slow or reverse trends. The combination of the Anthropocene paradigm and the planetary boundaries model suggests that all of humanity shares responsibility: only through massive collaboration – from local stewardship to global treaties – can biodiversity loss be halted and ecosystems preserved for future generations.

Pollution: Air, Water, Soil, and Plastics

Pollution is a pervasive global problem that degrades air, water, and soil quality, and increasingly includes synthetic chemicals and plastics as novel contaminants. Its sources are varied – industrial emissions, vehicle exhaust, agricultural runoff, untreated waste – but the impacts are consistently harmful to both the environment and human health. Below we briefly overview key categories of pollution.

- **Air Pollution:** Outdoor (ambient) air pollution, primarily fine particulate matter ($PM_{2.5}$) and ground-level ozone, causes substantial mortality and morbidity worldwide. Fossil fuel combustion (coal power plants, vehicle engines), biomass burning, and industrial processes emit particles and gases that irritate the respiratory system and enter the bloodstream. According to the World Health Organization, ambient air pollution contributes to **~7 million premature deaths per year** globally. Many developing cities regularly experience smog far exceeding WHO safety guidelines. Effects include heart disease, stroke, lung cancer, and aggravated asthma. Air pollution also deposits on soils and water bodies, carrying toxic metals. Notably, some air pollutants (e.g. black carbon soot, methane) also influence climate, so reducing air pollution can yield co-benefits for health and climate.
- **Water Pollution:** Water quality is compromised by sewage, agricultural runoff, industrial effluents, and chemical spills. Contaminated water is a major killer: about 1.7 billion people rely on drinking water sources contaminated with fecal bacteria or chemicals. Unsafe water and sanitation lead to waterborne diseases (cholera, diarrhea, typhoid) that cause roughly 1 million deaths per year. In agriculture, excess nitrogen and phosphorus from fertilizers pollute rivers and coastal zones, causing algal blooms and "dead zones" (oxygen-starved waters). Persistent organic pollutants (PCBs, pesticides) and heavy metals (lead, mercury) accumulate in fish and waterfowl, threatening wildlife and food safety. Even so-called "clean" water sources can contain emerging contaminants like PFAS and pharmaceuticals. Efforts such as wastewater treatment, agricultural best practices (buffer strips, precision farming), and bans on harmful chemicals are mitigating some risks, but in many regions water pollution remains a critical crisis.
- **Soil Pollution:** Industrial chemicals, pesticides, heavy metals and oil spills have degraded soils in many areas. For example, excessive use of the pesticide DDT or the metal lead has left long-lived residues in soils. Acid rain and salinization (from irrigation) have further degraded arable land. Polluted soils reduce fertility and crop yields, and can lead to contaminated food. Globally, hundreds of millions of hectares of soil are considered degraded by chemical pollution or erosion. Clean-up and sustainable land management (crop rotation, limiting agrochemicals, phytoremediation) are needed to recover soil health, but are not yet widespread enough.
- **Plastic Pollution and Novel Chemicals:** The production and disposal of plastics and other synthetic materials create a novel pollution category. Worldwide plastic production has exploded from 2 million tonnes in 1950 to roughly 460 million tonnes per year by 2019. Most plastic is durable and accumulates as waste. Only about **9%** of plastic has ever been recycled, with the rest landfilled, incinerated, or dumped. A small percentage (estimated 1–2 million tonnes annually) leaks into the oceans. This marine plastic injures wildlife and carries toxins: at least 267 marine species (turtles, seabirds, mammals, fish) are known to be harmed by plastic entanglement or ingestion. Microplastics have now been found in water, soils, and even the air, raising concerns about food chain contamination and health effects. Beyond plastics, countless "novel entities" – synthetic chemicals (pharmaceuticals, persistent organic pollutants, nanoparticles) – are entering ecosystems faster than we can assess them. The planetary boundaries framework warns that these novel chemicals represent an emerging risk beyond the other biogeochemical disruptions.

In response to these pollution problems, many countries and cities have enacted regulations. For air pollution, clean air acts (like the U.S. Clean Air Act or China's recent air quality laws) mandate emission controls on vehicles and factories. Water pollution is addressed by discharge permits, sewage treatment requirements, and wetland protections. Internationally, the Montreal Protocol eliminated most ozone-depleting chemicals (a success story) and also reduced powerful greenhouse gases (see Governance section). Plastic pollution is now on the global agenda too: several nations have banned single-use plastics, and multilateral discussions are underway for a possible treaty on plastics waste. Nevertheless, pollution remains a global problem because of uneven enforcement and the transboundary nature of air and water pollution (e.g. acid rain, plastic gyres in oceans). The pervasive nature of pollutants means that most ecosystems now contain human-derived chemicals, underlining that pollution is a fundamental part of the Anthropocene transformation of the environment.

Deforestation and Land Degradation: Causes, Impacts, Restoration

Drivers of Forest Loss and Land Degradation

Forests and soils are being lost and degraded at an alarming rate worldwide. The primary driver is **land conversion** for agriculture and pasture. Tropical deforestation is largely due to clearing land for cattle ranches, soybeans, oil palm, and other commodities. For instance, a recent FAO report notes that 40% of tropical deforestation (2000–2010) resulted from commercial agriculture (cattle, soy, palm oil), with another 33% from smallholder subsistence farming. In total, the world lost about 420 million hectares of forest since 1990 (nearly the size of the Amazon basin), although net losses have slowed somewhat recently. Logging – both legal and illegal – adds to tree loss; wood fuel gathering also degrades forests in many countries. Rapid expansion of urban areas and infrastructure (roads, dams, mines) further fragments and consumes forest land.

Similarly, land degradation (the loss of land productivity) is driven by unsustainable farming, overgrazing, deforestation, and poor water management. Over-cultivation and monoculture deplete nutrients; overgrazing by livestock compacts soil and kills native grasses; irrigation without proper drainage leads to salinization. Desertification – the spread of deserts – is a severe case of land degradation, especially in drylands. Globally, an estimated 100 million hectares of productive land are lost each year to degradation. This trend is worsening: since 2015, regions like sub-Saharan Africa, Western Asia, and Latin America are seeing land degradation accelerate by 6–8 percentage points above the global average. Key crops in these areas face declining yields, creating food security challenges. Climate change (drought, extreme rainfall) and wildfires exacerbate land degradation. In sum, by altering the land's natural state, humanity is undermining the very resource base needed for agriculture, water regulation and climate stability.

Impacts of Forest and Soil Loss

The impacts of deforestation and degradation are multifaceted. Forests store vast amounts of carbon; cutting them releases CO_2. Roughly 10–15% of anthropogenic carbon emissions come from deforestation and peatland loss. The Amazon rainforest, often called the "lungs of the Earth", has already begun emitting more CO_2 than it absorbs during extreme drought years. Loss of tree cover also disrupts local and regional climate: forests recycle moisture back into the atmosphere, so deforestation can reduce rainfall and exacerbate drought. Biodiversity suffers: tropical forests are among the most species-rich ecosystems, so their removal directly causes extinctions and fragmentation effects on wildlife. Soil is lost with trees: deforested slopes erode, sending sediment into rivers and reducing fertile topsoil. In the long run, degraded lands yield less food or become unusable, threatening livelihoods of rural populations. Economically, studies suggest that land degradation affects up to half of global GDP – much of agriculture and ecosystem services depend on healthy lands. A recent statement by UNEP emphasizes that billions of hectares are already degraded, impacting nearly half the world's population and jeopardizing roughly half of global economic output.

The combination of deforestation and land degradation also creates negative feedbacks. Exposed soil emits more dust and can contribute to atmospheric warming (by reducing albedo). Degraded lands hold less water, making floods worse. In many cases, short-term economic gains from clearing land (e.g., crop production) are offset by long-term losses in productivity and resilience.

Restoration and Sustainable Land Use

Reversing deforestation and degradation requires concerted effort at multiple scales. International initiatives have emerged: the Bonn Challenge is a global effort to restore 350 million hectares of deforested and degraded lands by 2030. As of the latest reports, countries and organizations have pledged to restore about 210 million hectares under this and related commitments. Governments also declared the UN Decade on Ecosystem Restoration (2021–2030) to prevent, halt and reverse land degradation across forests, wetlands, farmlands and more. Notably, countries have collectively pledged to restore one billion hectares of ecosystems (an area larger than China). These ambitious goals reflect growing recognition that ecological restoration is crucial for climate mitigation (trees sequester carbon), biodiversity conservation, and human welfare.

On the ground, restoration practices include reforestation and afforestation (planting new trees), but also agroforestry (integrating trees into farms), natural regeneration (protecting areas to allow forests to regrow), and grassland rehabilitation. Community-led initiatives, such as farmer-managed natural regeneration in the Sahel region, have shown promise in re-greening landscapes. Restoring mangroves and coastal wetlands can protect shorelines and nursery habitats for fish. To make forests sustainably managed, practices like selective logging, legal enforcement against illegal clearing, and recognition of indigenous land rights are essential. Indigenous-managed forests often have lower deforestation rates, highlighting the importance of land tenure and community stewardship.

Policy instruments are being employed: paying farmers and landowners for ecosystem services (carbon credits, payments for watershed protection), enforcing zero-deforestation supply chain commitments (e.g. in beef or palm oil sectors), and promoting sustainable agricultural intensification on existing farmland to reduce the pressure to clear more land. The concept of land degradation neutrality (LDN) has been promoted by the UN Convention on Combating Desertification: countries aim to balance degraded land with restored land by 2030. For example, some countries have adopted "mosaic restoration" of forests and farms, and invest in erosion control (terracing, cover crops) to stabilize soils.

Financial support is critical. Developed nations and multilateral funds (like the Green Climate Fund or the Global Environment Facility) provide billions of dollars for REDD+ (Reducing Emissions from Deforestation and forest Degradation) and restoration projects in the tropics. Nevertheless, these funds are still a fraction of what is needed. The scale of restoration required means that agriculture must become more sustainable overall – with less waste, more efficient irrigation, and diets that are less land-intensive (e.g. reduced meat consumption) – to relieve pressure on forests.

In summary, deforestation and land degradation stem largely from agricultural expansion and unsustainable practices. The consequences—carbon emissions, biodiversity loss, soil erosion, and economic damage—are severe. However, restoration science shows that well-designed efforts can recover landscapes. By adopting sustainable land management, expanding restoration commitments (the "1B ha" goal), and supporting agroecological practices, it is possible to reverse some losses. This is an area of active international cooperation and domestic policy innovation, reflecting the broader recognition that forest and soil health are vital to solving the climate-biodiversity nexus.

Freshwater and Oceanic Challenges

Freshwater Resources: Scarcity, Quality, and Extremes

Fresh water is essential for life, yet its availability and quality are under growing stress worldwide. Freshwater scarcity arises from overuse and uneven distribution of water. Agriculture consumes roughly 70% of global freshwater withdrawals, mainly for irrigation; industry and domestic uses account for most of the rest. Groundwater provides about 25% of irrigation water and 50% of drinking water withdrawal. Population growth and economic development have steadily increased water demand by about 1% per year. As a result, many regions face chronic water stress: an estimated half of the world's population experiences severe water scarcity for at least part of the year. Large areas of Asia, the Middle East, Africa, and parts of the Americas withdraw more water than flows can replenish, depleting rivers and aquifers. The United Nations World Water Development Report highlights that water deficits have historically driven migration: during 1970–2000, water scarcity was linked to a 10% rise in migration globally. Climate change exacerbates scarcity through shifting rainfall patterns and more frequent droughts. Meanwhile, water infrastructure (dams, canals) often fails to distribute water equitably, and pollution makes some available supplies unusable without treatment.

Water quality is another concern. In many developing regions, poor sanitation and lack of clean water sources lead to contamination. As noted earlier, some 1.7 billion people drink water contaminated with fecal matter. This contributes to waterborne illnesses; the WHO reports roughly 1 million diarrheal deaths per year from unsafe water, sanitation and hygiene. In higher-income areas, agricultural runoff (fertilizers and pesticides) is often the primary pollutant, causing algal blooms and heavy metal poisoning in fisheries. Industrial discharges can dump toxic chemicals into rivers and lakes. The cumulative effect is that even ostensibly "clean" rivers can contain pharmaceuticals, microplastics, or heavy metals at harmful levels. Cleaning up water requires both upstream controls (wastewater treatment, agricultural best practices) and source protection (e.g., preserving forested watersheds), but progress is mixed. For example, despite billions spent on treatment, wastewater coverage remains incomplete in many countries.

Water-related extreme events are also on the rise. Floods and droughts, exacerbated by climate change, impose severe impacts. UNESCO's analysis notes that floods over 2002–2021 caused nearly 100,000 deaths (plus 8,000 in 2022), affected around 1.6 billion people, and inflicted some US$832 billion in economic losses. Droughts over the same period affected 1.4 billion people, caused more than 21,000 deaths, and $170 billion in losses. In 2022 alone, catastrophic floods hit Pakistan and Australia, while drought devastated parts of Africa and South America, illustrating how the hydrological cycle is intensifying. These events highlight that managing water risks – through infrastructure (reservoirs, levees), early warning, and ecosystem-based adaptation (wetland restoration for flood control) – must be part of the response.

Overall, the combination of scarcity, contamination, and extremes means water security is a global challenge. The Sustainable Development Goal 6 (clean water and sanitation) is far off target: by 2022 about 2.2 billion people still lacked safely managed drinking water. Solutions range from investing in efficient irrigation and drought-resistant crops, to scaling up desalination and water recycling, to enforcing strict pollution controls. Transboundary cooperation is also critical: most major rivers and aquifers cross national borders, so countries must negotiate sharing and joint management (e.g. Nile, Mekong, Indus basins). In sum, ensuring sustainable freshwater supply and quality for a growing population in a changing climate is a central 21st-century challenge.

Oceanic Issues: Acidification, Overfishing, and Marine Pollution

The world's oceans – covering 71% of Earth's surface – face severe stressors from climate change and human use. A key chemical change is ocean acidification. The oceans absorb roughly one-third of human-emitted CO_2. When CO_2 dissolves in seawater, it forms carbonic acid, lowering pH. Since pre-industrial times, the average pH of surface ocean water has dropped from about 8.21 to 8.10. While this 0.1-unit change seems small, it corresponds to a 25% increase in acidity. This is occurring at a rate unprecedented in millions of years. Acidification reduces carbonate ions that marine organisms (corals, shellfish) need to build shells and skeletons, threatening reef ecosystems and mollusk fisheries. Along with warming, acidification is already contributing to widespread coral bleaching and reef decline in places like the Great Barrier Reef and Caribbean. Projections indicate that under high-CO_2 scenarios, surface ocean waters could become corrosive to carbonate shells by mid-century, endangering food webs and coastal economies.

Overfishing and biodiversity loss are another major threat in the seas. The FAO estimates that over 90% of global fish stocks are fully fished or overfished (33% overfished, 60% at full sustainable yield). Decades of industrial-scale fishing have removed massive biomass from the ocean; global seafood consumption has doubled in the last 50 years. Critical predators (e.g. large tuna, sharks, tunas) and forage fish are greatly depleted, which cascades through ecosystems. Many fisheries collapse when catches fall below economic viability. Overfishing not only threatens food security for communities dependent on fish; it also alters marine ecosystems, potentially leading to regime shifts (e.g. from fish-dominated to jellyfish-dominated systems). Although some fisheries management practices have improved (catch limits, marine protected areas), the overall trend remains worrisome. Aquaculture has expanded (now ~50% of fish consumed), but it often relies on wild fish for feed, so it has not fully relieved pressure on wild stocks.

Marine pollution compounds these problems. Besides oil spills and chemical runoff, the previously mentioned issue of plastic is acute in oceans. The equivalent of 1–2 million tonnes of plastic (0.5% of global plastic waste) enters the marine environment each year. Ocean currents concentrate plastic debris in gyres (e.g. the Great Pacific Garbage Patch). Marine plastic fragments into microplastics that have been found in plankton, fish, and even table salt. Floating plastic entangles wildlife, and ingestion (seen in turtles, seabirds, whales) can be fatal. As noted, at least 267 marine species are documented as being affected by plastic pollution. Other pollutants, such as persistent pesticides and PCBs, accumulate in marine food webs, leading to contamination of seafood and toxicity in marine mammals. Nutrient runoff from land creates coastal "dead zones" (low-oxygen waters) by fueling algal blooms that die and decompose, using up oxygen. Examples like the Gulf of Mexico dead zone illustrate the impact on fisheries.

Finally, sea-level rise and changing ocean circulation patterns (both aspects of climate change) pose existential threats to coastal zones and islands. Melting glaciers and expanding warmer ocean water are causing global mean sea level to rise by about 3–4 mm per year currently, affecting millions of people in low-lying deltas and small island states. Saltwater intrusion threatens groundwater and agriculture in coastal areas. Ocean heatwaves (marine heatwaves) are killing kelp forests and coral in many regions, further stressing marine biodiversity.

In response, international efforts include the UN Convention on the Law of the Sea and Regional Fisheries Management Organizations to govern use of the high seas. The International Maritime Organization has set targets to reduce shipping emissions (methane and black carbon) to curb polar warming. Locally, nations are establishing marine protected areas (MPAs) to allow stocks to recover – though currently only about 8.4% of the ocean is protected. The UN has begun negotiations on a High Seas Biodiversity Treaty to better conserve areas beyond national jurisdiction. Technological fixes include development of selective fishing gear to reduce bycatch, and initiatives to clean up plastics (e.g. The Ocean Cleanup project). While these measures show promise, the scale of the challenge – acidifying waters, warming seas, exhausted fisheries – means concerted global action (e.g. cutting CO_2 for acidification, enforcing sustainable fisheries) is essential. In short, the freshwater and oceanic dimensions of the crisis highlight that water – whether on land or at sea – is subject to severe stressors, and that protecting these resources is critical for climate resilience and human survival.

Global Environmental Governance and Solutions

The scale of these crises has driven a proliferation of international and national responses. Effective solutions hinge on coordinated governance across borders, combining treaties, policies, finance, and innovative frameworks. Below we outline key elements of global environmental governance and emerging models of sustainability.

- **Treaties and Agreements:** Multilateral environmental agreements are the backbone of global governance. The most prominent is the UN Framework Convention on Climate Change (UNFCCC), under which the Paris Agreement (2015) [30] commits virtually all countries to limit warming to well below 2°C (aiming for 1.5°C). Although current pledges under Paris still imply ~2.3–2.5°C of warming, the Agreement provides a regular "global stocktake" process to ratchet up ambition. The Montreal Protocol (1987), originally targeting ozone-depleting substances (ODS), is widely hailed as a success. Parties have already phased out about 98% of ODS globally, which is also preventing a massive release of CO_2-equivalent greenhouse gases. With continued implementation, the ozone layer is expected to recover by mid-century. Notably, Montreal has been extended via the Kigali Amendment to phase down hydrofluorocarbons (HFCs), potent climate forcers, which will yield significant climate benefit. Other conventions cover specific realms: the Convention on Biological Diversity (CBD) sets biodiversity targets (such as the "30×30" protection goal), the UN Convention to Combat Desertification (UNCCD) focuses on land, and regional agreements (e.g. the Ramsar Wetlands treaty, various fisheries agreements) protect particular ecosystems. On toxic chemicals, the Stockholm and Rotterdam Conventions regulate persistent organic pollutants and hazardous pesticides. Trade measures (e.g. tariffs on illegal timber or fisheries products) have also been used.
- **Sustainable Development Goals (SDGs):** The 2030 Agenda for Sustainable Development, adopted by all UN member states, integrates environmental objectives with social goals. Several SDGs relate directly to the environment: for example, SDG 13 (Climate Action), SDG 14 (Life Below Water), SDG 15 (Life on Land), plus clean water (SDG 6) and clean energy (SDG 7). These goals provide a broad framework for national policies. Progress on the SDGs has been uneven, but they serve as a unifying global vision. Importantly, they emphasize that poverty eradication and development must go hand-in-hand with environmental protection.
- **International Cooperation and Finance:** Addressing global issues requires funding and technology transfer. Mechanisms like the Green Climate Fund aim to channel climate finance to vulnerable countries. The Global Environment Facility and multilateral development banks fund conservation and clean energy projects. Initiatives such as *REDD+* (Reducing Emissions from Deforestation and Degradation) create financial incentives for forest protection. International scientific bodies (IPCC for climate, IPBES for biodiversity) foster data sharing and consensus. Regions collaborate through coalitions: for instance, the High Ambition Coalition in climate, or regional fisheries management bodies for ocean resources. Public–private partnerships, multistakeholder platforms, and transnational networks (like the C40 cities network for climate action) are also emerging forms of governance.
- **Economic and Policy Instruments:** Many governments have instituted policies aimed at sustainability. Carbon pricing (either carbon taxes or cap-and-trade) is one major tool: over 60 jurisdictions have implemented some form of carbon pricing, covering a significant share of global GDP. Subsidy reforms (removing fossil fuel subsidies) can redirect capital toward renewables. National laws enforce pollution standards (clean air/water acts), protected area designations, and building codes for energy efficiency. On the economic model side, concepts like the circular economy are gaining traction: they emphasize waste reduction and resource recirculation. Corporate sustainability initiatives (e.g. RE100 commitments by major companies to use 100% renewable energy) also reflect governance from the private sector. While voluntary, these can influence markets.
- **Technological and Nature-Based Solutions:** Innovation is a key solution avenue. Clean energy technologies (solar, wind, batteries) have scaled up globally: indeed, renewables now account for over 30% of the world's electricity, a dramatic increase from a decade ago. Electric vehicles are displacing fossil-fuel transport in many countries. Advances in remote sensing and AI improve ecosystem monitoring and enforcement. Meanwhile, *nature-based solutions* – leveraging natural processes – are advocated widely. Examples include coastal mangrove restoration for flood protection, urban green spaces for air quality, and reforestation to sequester carbon. Financial institutions are increasingly evaluating environmental risks; for example, some central banks are stress-testing financial systems for climate risks. These trends show that sustainability is gradually entering mainstream economics and planning.
- **Policy Models and Ethics:** Underlying these practical measures are broader sustainability frameworks. The concept of the "Green Economy" advocates decoupling growth from environmental impact, through sustainable production and consumption patterns. The circular

economy model specifically targets resource loops (e.g. recycling, product-as-a-service). International declarations, such as the 2022 "Glasgow Leaders' Declaration on Forests and Land Use," set ambitions (zero deforestation by 2030, restoration targets). There is also growing emphasis on equity and justice: the rights and knowledge of Indigenous peoples and local communities are increasingly recognized as vital for effective conservation. Major conferences (like UN Environment Assembly or the World Conservation Congress) set normative agendas. The COVID-19 pandemic and the concept of "One Health" have further highlighted links between environmental health and human health, pushing for more integrated policies.

In practice, the effectiveness of governance varies. The Montreal Protocol's success shows that a strong science-policy agreement, universal participation, and support mechanisms (like the Multilateral Fund) can achieve environmental turnaround. By contrast, climate pledges under Paris are far from sufficient, requiring renewed ambition. As one assessment notes, current national commitments still leave a large gap to keep warming under 2°C. This underscores a persistent challenge: aligning short-term economic interests with long-term global good. Even so, there is cautious optimism. For instance, widespread adoption of net-zero targets and the rapid cost decline of green technologies suggest a structural shift. Many experts believe that integrating sustainability into economic recovery plans (post-COVID stimulus, for example) can accelerate the transition.

In conclusion, global environmental governance encompasses a multi-layered array of treaties, policies, and cooperative efforts. The scale of environmental threats has led nations to articulate ambitious goals (like the SDGs and 30×30 biodiversity target), but meeting these goals will require far-reaching implementation. Key trends – renewable energy surges, expansion of protected areas, and growing restoration pledges – show that solutions are beginning to take shape. Yet, the science is clear that without stronger and faster action, we risk surpassing planetary boundaries and locking in irreversible damage. Ultimately, achieving sustainability will depend on sustained international cooperation, innovation, and a willingness to transform human systems. Global environmental governance provides the framework, but it must translate into real-world change if it is to steer the Anthropocene onto a safe pathway.

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