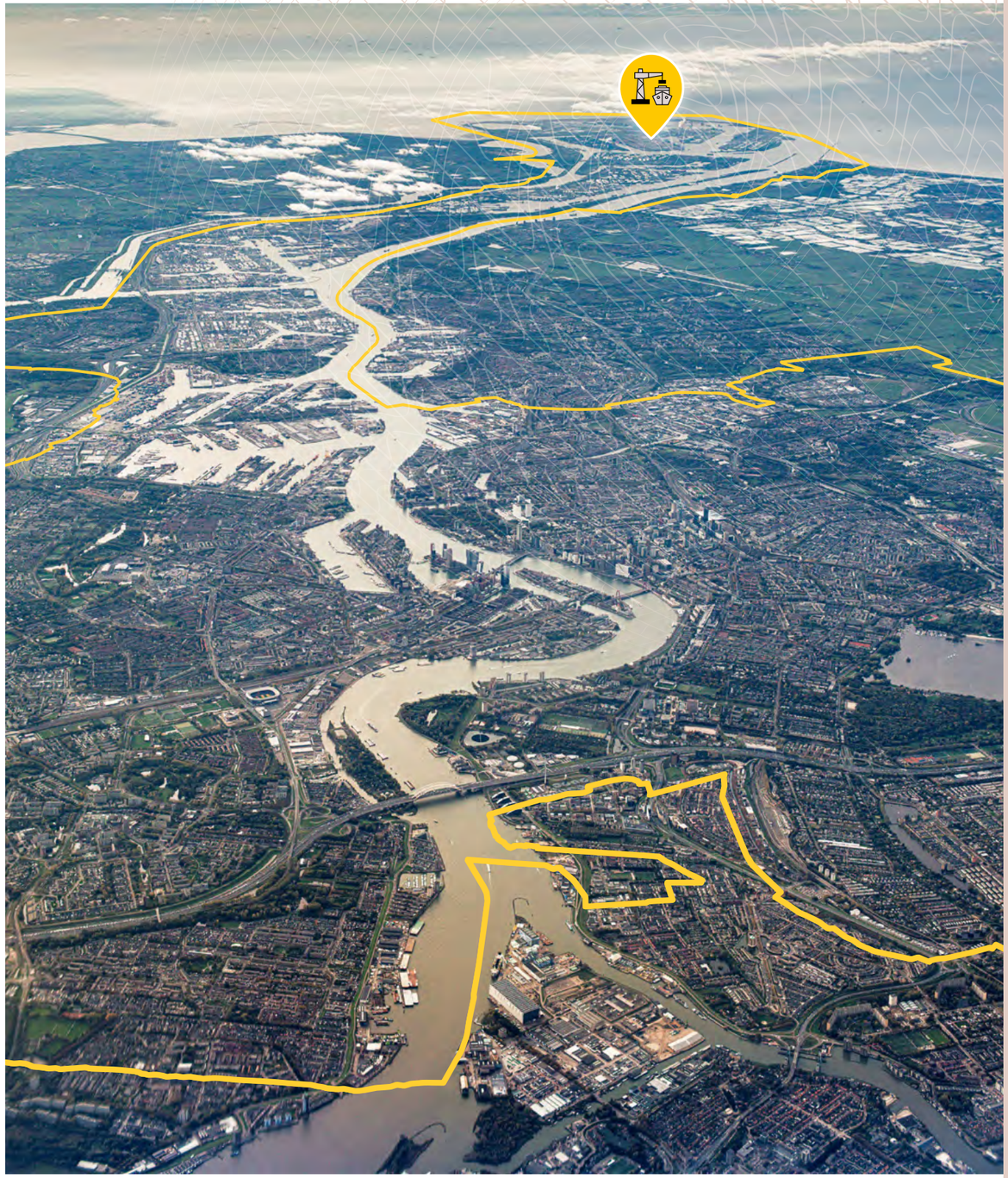
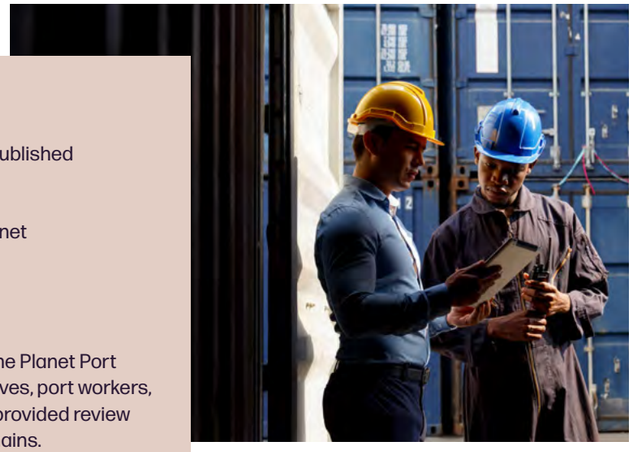
Port of Rotterdam, thriving within the Planetary Boundaries

A One Planet Port vision





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Disclaimer: This Vision Report draws on the best available science but does not attempt to review all literature on the Planetary Boundaries or related fields. The concepts and methods presented here are evolving, and we welcome feedback to improve future editions.

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Executive Summary

This Vision Report sets out a strategic, systems-level roadmap for transforming the Port of Rotterdam into a **One Planet Port** – a port that generates shared prosperity while operating safely within Earth's ecological limits. Using the Planetary Boundaries Framework, the report provides direction for aligning port development, maritime operations and trade flows with global environmental stability. It complements existing regulatory and disclosure frameworks such as the CSRD, CSDDD, EU Taxonomy, the GHG Protocol and forthcoming EU Ports Strategy with the EU Clean Industrial Deal offering systems-level thinking that identifies synergies, gaps, and potential unintended consequences across interconnected environmental domains.

Ports are both contributors to planetary instability and highly exposed to it. Climate extremes, ocean degradation, air pollution and resource-intensive global value chains increasingly threaten economic and environmental resilience and public well-being. Yet within this instability lies a defining opportunity. The Port of Rotterdam, given its scale, world-class logistics capacity, and rapidly advancing capabilities in materials and value-chain mapping, can demonstrate how a major port can restore nature, cut systemic risks, and support high-quality jobs while reducing pressures across all nine planetary boundaries.

This report outlines how transformation can be achieved by shifting from high-throughput, resource-intensive trade towards circular, regenerative and sufficiency-based economic activity. It calls for design and decision-making that are framed within ecological limits, moving from incremental initiatives to system-wide change.

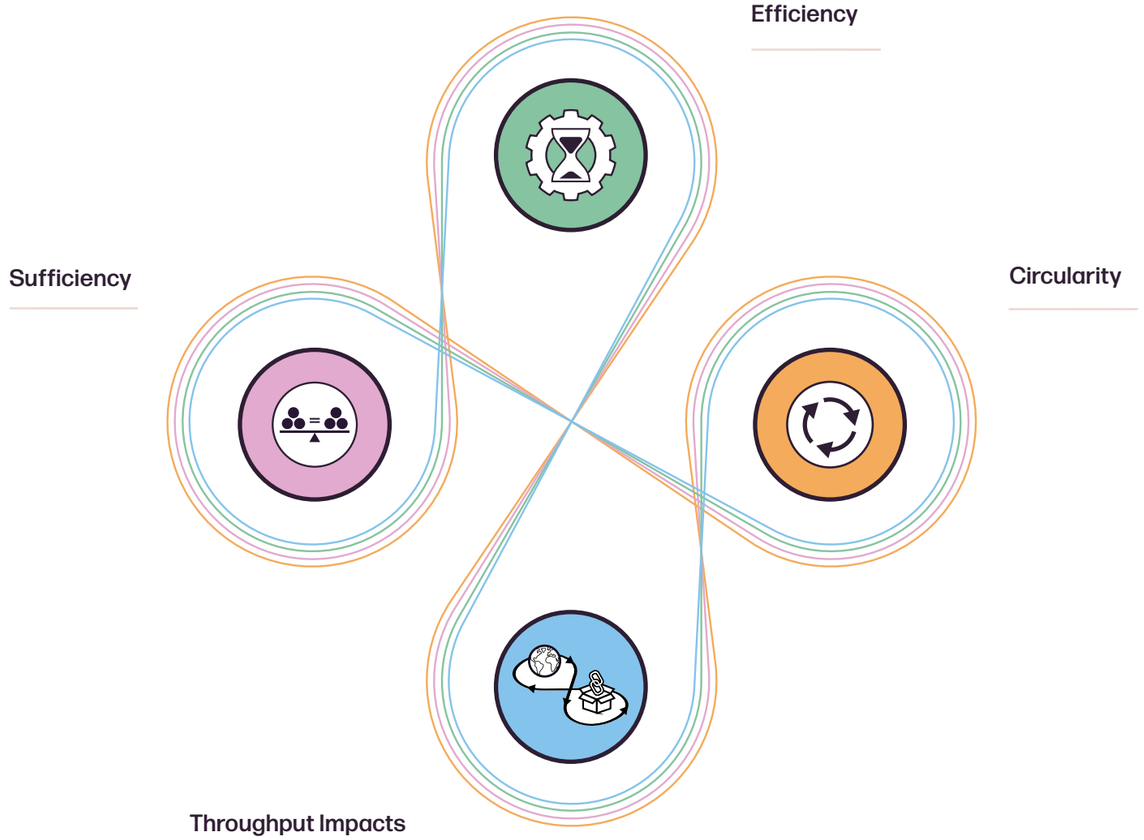
Organised around the nine planetary boundaries, each chapter moves from global scientific status to national context, to port-specific pressures, feasible maritime interventions, current Port of Rotterdam actions, and targeted recommendations for both the Port Authority and policymakers. This structure ensures that evidence-based insights translate into practical, implementable pathways.

The Vision culminates in a multi-principle framework for a regenerative port built on:

- **Efficiency** – optimising resource and energy use within planetary limits
- **Sufficiency** – meeting needs without excess or unnecessary throughput
- **Circularity** – shortening and closing resource loops to enhance resilience
- **Throughput Impacts** – assessing the full planetary boundaries pressures embodied in the goods moving through the port, from production to transport to end-of-life

Finally, the report is intentionally directional rather than prescriptive, establishing foundations for next-phase collaborative work that will develop detailed implementation pathways including port-wide energy–material flow accounting, sufficiency-based access criteria, a circular cluster pilot zone, and a workforce transition fund – demonstrating that ecological regeneration and economic vitality can reinforce one another.

We offer this analysis as an open invitation for dialogue and knowledge-sharing towards building regenerative port ecosystems, in cooperation with sector experts and policymakers, that safeguards both our planetary systems and human well-being. Together we can make it happen.



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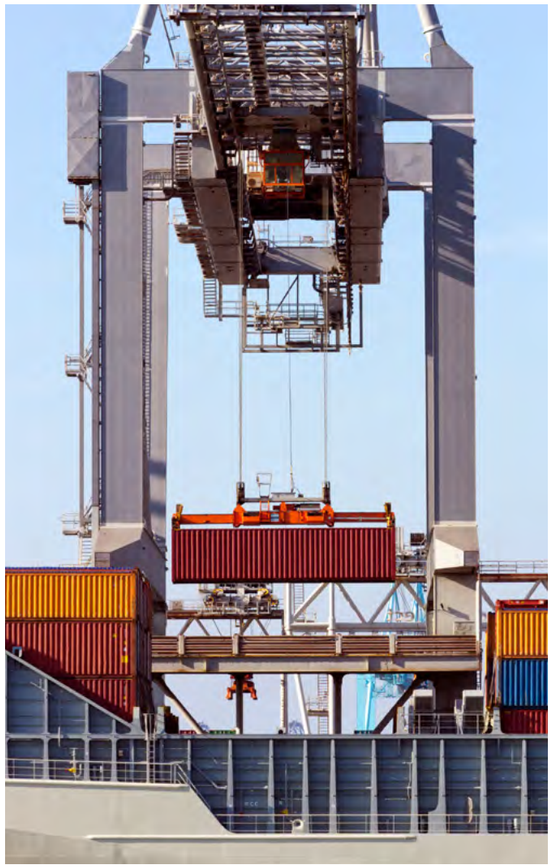

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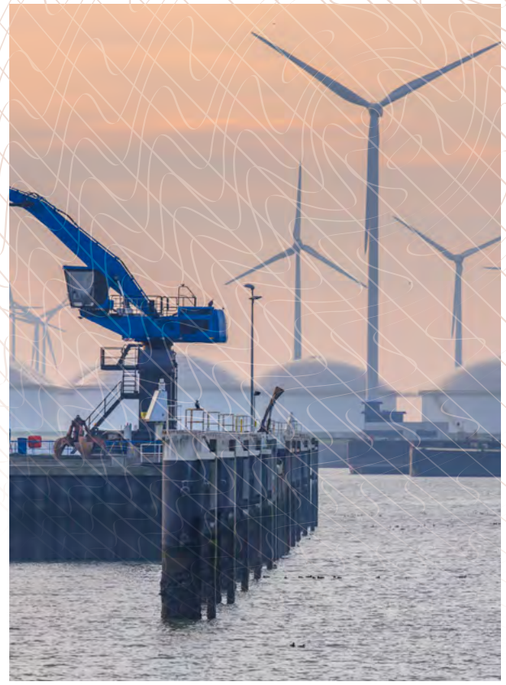


CH1 Introduction

From Port to Possibility: Rotterdam's One Planet Opportunity

This report shows how a great port can create broad prosperity while restoring the nature it depends on. Rotterdam and the port have what it takes: public ownership and accountability that enable long-term planning in the public interest with world-class logistics and engineering, research depth, a culture of hands-on innovation, and communities determined to secure healthy air, water, and jobs

Imagine clean air across port-city neighbourhoods, thousands of skilled jobs in electrification and circular servicing, reliable trade resilient in the face of heat, wind, and water issues, and a living waterfront where biodiversity returns.

This is the essence of a **One Planet Port**, a port that delivers shared prosperity by operating within ecological limits, regenerating the systems that make well-being possible.

Why Now, and Why Rotterdam?

Global shifts are already here, and they favour places that move first. Companies, financiers, workers, and citizens are aligning around resilience and fair value chains. The Port of Rotterdam's scale, public mandate, and track record mean actions taken here echo across Europe and globally. When Rotterdam demonstrates a port can be clean, circular, sufficient, and collaborative, Europe can follow.

The Stakes – Briefly and Clearly.

Environmental instability is now a security and prosperity risk. Rising seas and extreme weather interrupt operations, ocean degradation weakens life-support functions, and supply chains feel the strain. The longer we delay, the higher the costs. The good news — the same investments that cut risk (efficiency, electrification, circular flows, and nature-based protection) also build resilience, improve health, and strengthen cooperation among port partners.

From Risk to Roadmap.

Ports are both contributors and exposed to environmental instability. That makes them powerful leverage points for regeneration. By aligning port decisions with the **Planetary Boundaries Framework**, Rotterdam can reduce systemic risk while unlocking durable, collaboratively built prosperity.

Our roadmap is practical:

1. Design and operate within planetary limits.

2. Prioritise absolute reductions in harm.

3. Make nature an ally.

4. Ground value chains in transparency and fairness.

Facing Instability with Purpose

Even as Rotterdam stands ready to lead, we cannot ignore the scale of the challenge ahead. Across Europe and the world, environmental risk has become a security risk. The accelerating breach of ecological planetary boundaries — from climate change and biodiversity loss to freshwater depletion, ocean acidification and chemical pollution — is eroding the natural systems that underpin prosperity and peace. Rising seas threaten critical infrastructure, extreme weather disrupts supply chains, and ecosystem declines undermine food, water and health security. Resource scarcity already drives tension and instability across regions. Scientific evidence shows that several Earth system processes are now approaching or crossing tipping points that could trigger irreversible shifts in the biosphere. These cascading effects create profound uncertainty, weakening the very foundations of economic stability and social cohesion upon which European well-being and prosperity depends.

Around 80 percent of world trade by volume moves by sea, and Europe's major ports, including Rotterdam, Antwerp-Bruges, and Hamburg, are critical nodes in this system

Nowhere are these pressures felt more clearly than in the maritime sector, the backbone of global trade and the circulatory system of the global economy. Around 80 percent of world trade by volume moves by sea[1], and Europe's major ports, including Rotterdam, Antwerp-Bruges, and Hamburg, are critical nodes in this system, enabling Europe's imports, exports, and energy security. Yet, they are increasingly vulnerable to systemic environmental shocks. Climate-driven sea-level rise and extreme weather threaten port infrastructure, while biodiversity loss and ocean acidification erode the natural and material foundations of maritime operations. About half of the oxygen we breathe originates from the ocean, sustained by plankton, drifting plants, algae, and bacteria that can photosynthesise[2]. These are now under stress from warming, acidification and pollution, reminding us that the very systems supporting port economies also sustain life itself. The consequences of these systems destabilising are not only ecological but also economic. It is estimated that US$81 billion in global trade and at least US$122 billion in economic activity are at risk annually from disruptions to critical ports as a result of climate extremes[3], underscoring how closely Europe's security and prosperity depend on the health of planetary systems.

Within this Crisis Lies a Defining Opportunity

Recognising ports as both contributors to and victims of environmental instability reframes them as powerful leverage points for planetary regeneration[4*]. By embedding planetary boundary thinking into infrastructure planning and trade policy, aligning port operations with ecological limits, and fostering cross-border collaboration, Europe can turn vulnerability into strength. Through coordinated resilience[5†], adaptation[6‡], and mitigation[7§] efforts, European ports[¶] can evolve from vulnerability hotspots into strongholds of security and regeneration.

* A regenerative system is one in which resource input and waste, emission, and energy leakage are minimised by slowing, closing, and narrowing energy and material loops. *https://business.edf.org/insights/pathways-to-net-zero-circular-economy-strategies-for-climate-action/*

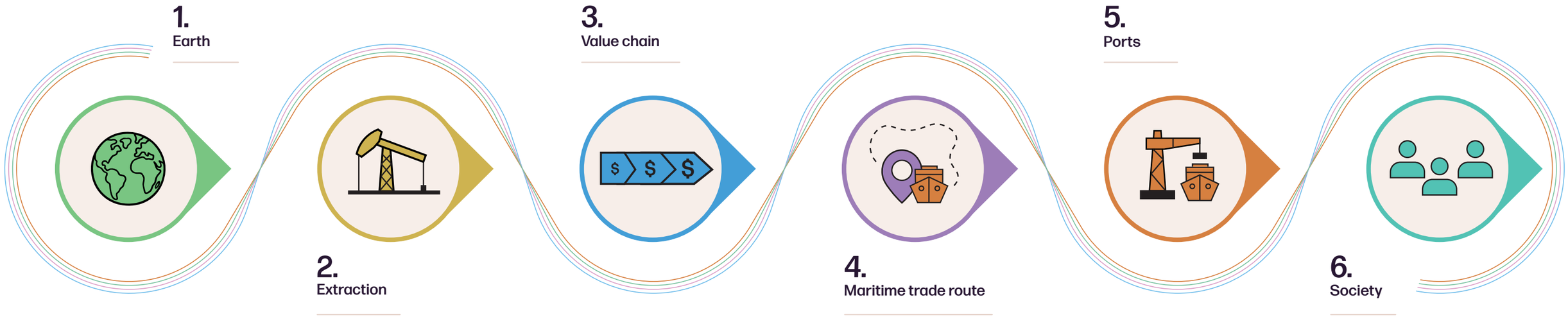
† Climate resilience is the ability to anticipate, prepare for, and respond to hazardous events, trends, or disturbances related to climate. Improving climate resilience involves assessing how climate change will create new, or alter current, climate-related risks, and taking steps to better cope with these risks *https://www.c2es.org/content/climate-resilience-overview*.

‡ Climate change adaptation refers to actions that help reduce vulnerability to the current or expected impacts of climate change like weather extremes and hazards, sea-level rise, biodiversity loss, or food and water insecurity. *https://climatepromise.undp.org/news-and-stories/what-climate-change-adaptation-and-why-it-crucial*

§ Climate change mitigation refers to any action taken by governments, businesses or people to reduce or prevent greenhouse gases, or to enhance carbon sinks that remove them from the atmosphere. These gases trap heat from the sun in our planet's atmosphere, keeping it warm. *https://climatepromise.undp.org/news-and-stories/what-climate-change-mitigation-and-why-it-urgent*

¶ A port that is resilient can withstand disruptions, adaptation measures help it adjust to changing conditions, and mitigation efforts reduce the severity of future climate change impacts.

Figure 1.1 Logic chain



Who is the One Planet Port (OPP) Foundation?

OPP unites communities, workers, researchers, and policymakers to reimagine port activity, restoring nature, protecting health, and supporting good jobs that align with a liveable planet. OPP aims to create a clear vision and stepwise roadmap for transforming the Port of Rotterdam into a port that prioritises and substantiates value chains based on material sufficiency — those that meet genuine needs while operating within planetary boundaries. This means shifting the port's role from facilitating high-throughput, resource-intensive trade towards enabling circular, regenerative, and socially just economies that build environmental security and resilience through democratic collaboration[8].

The concept of a One Planet Port represents a decisive shift from conventional port development. Building on the principles of One Planet Living[9] and UN One Health[10], and aligned with the UN One Planet Network[11], it extends their core message to the maritime domain — that human activity must remain within the ecological means of a single planet. A ***One Planet Port*** envisions regenerative infrastructure and sufficiency material throughput, that operates within Earth's limits while restoring degraded ecosystems, safeguarding biodiversity, and sustaining the foundations of trade and human well-being. Rather than extracting value from natural systems, these ports actively regenerate ecological health while maintaining their essential economic functions. Inspired by the One Planet Shipping Report[12], this approach recognises that lasting societal prosperity depends not on consuming and depleting Earth's life-support systems but on strengthening them through operations that remain within, and help uphold, planetary boundaries.

This Vision Report provides strategic direction for policymakers and port decision-makers navigating the complex interconnections between planetary boundaries and maritime operations. Rather than prescribing quantitative targets, this document seeks to illuminate the systemic relationships between port activities and Earth's life-support systems, showing how actions in one domain inevitably reverberate across others. Our analysis demonstrates that siloed approaches to environmental management risk unintended consequences that can undermine both planetary health and human security and well-being. By mapping these interdependencies across the Earth's environmental boundaries, OPP provides European policymakers with the systems-thinking tools needed to design integrated port transformation strategies that enhance, rather than erode, ecological resilience.

This document aims to support decision-makers in navigating trade-offs, identifying synergies and avoiding the pitfalls of fragmented environmental policies. We offer this framework to help the City and Port of Rotterdam, and port-city systems worldwide, move from isolated, issue-specific initiatives towards holistic, interconnected approaches that reflect the shared reality of ports and maritime systems operating within ecological limits.

Rotterdam: Europe's Gateway to Planetary Transformation

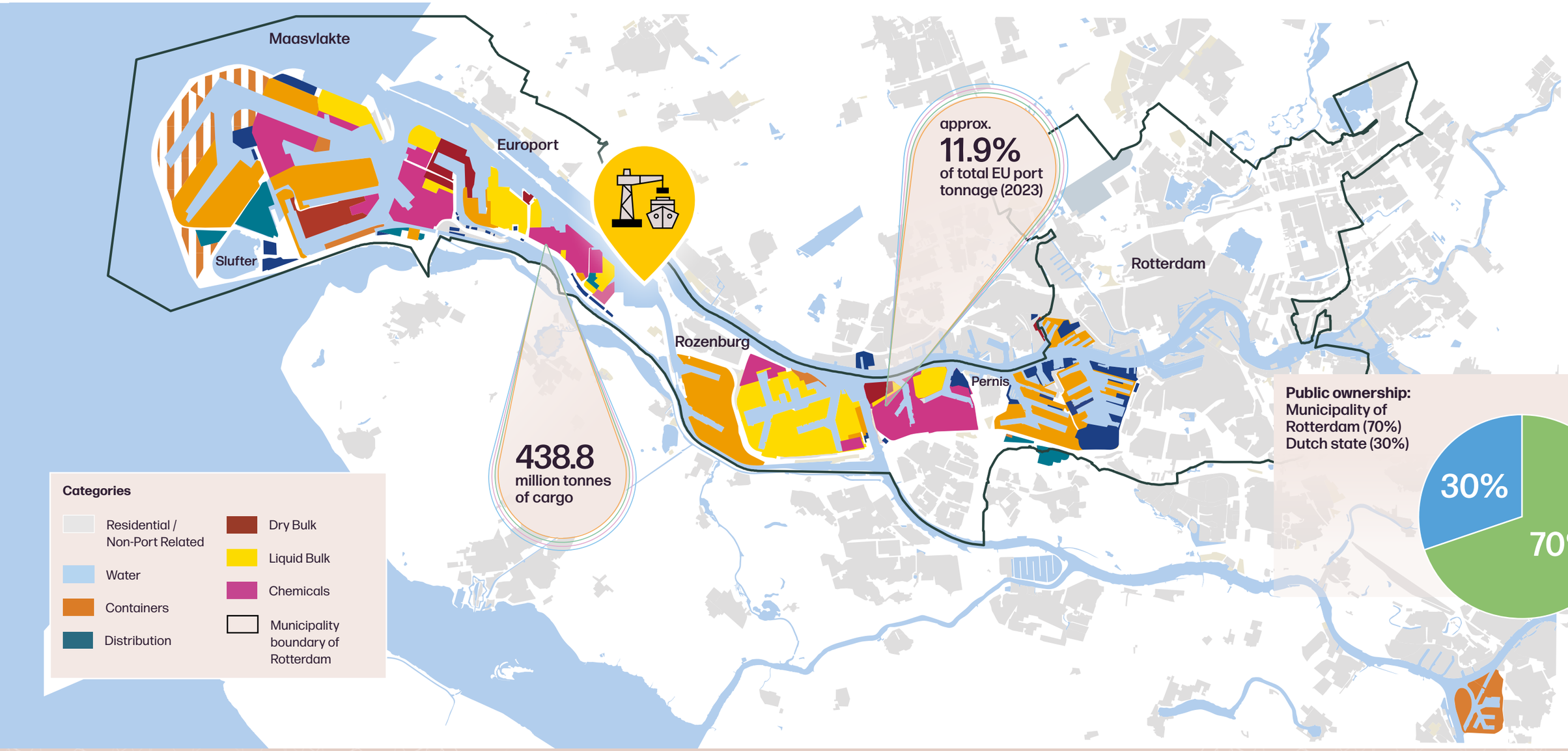
The Port of Rotterdam provides an unparalleled foundation for this transformative vision. As Europe's largest port[13], with a throughput of 438.8 million tonnes of cargo[14] and handling approximately 11.9% of total EU port tonnage in 2023[15], Rotterdam represents a critical node in global supply chains. Its scale and influence mean that any transition achieved here will reverberate across the Netherlands, Europe, and the global maritime system, advancing shared environmental and sustainability objectives.

Public ownership provides unique advantages. Shares in the Port of Rotterdam N.V. are held by the Municipality of Rotterdam (70%) and the Dutch state (30%)[16], ensuring that the port's strategic direction serves the public interest. This governance structure helps safeguard nautical safety, efficient land use and environmental stewardship, while enabling long-term planning beyond quarterly profit cycles – a prerequisite for systemic transformation aligned with the planetary boundaries.

Rotterdam's challenges mirror those of major European ports. Rising sea levels, extreme weather, degraded air quality, and the urgent need to achieve deep greenhouse gas reductions while ensuring economic vitality and public value, and the well-being of the people living in the larger port area, are all issues being tackled by ports across the continent. Despite robust flood defences including elevated port areas and storm surge barriers, Rotterdam faces increasing risks from accelerating sea-level rise that could eventually exceed current protection levels[17]. Moreover, industrial activities within and around the port shape broader regional development patterns, reinforcing the importance of solutions that integrate ecological resilience, economic renewal, and social health. Pragmatic, system-wide strategies developed in Rotterdam can thus inform and inspire Europe's entire port network.

Global relevance ensures maximum impact: The innovations to be pioneered in Rotterdam – from circular logistics and material-sufficiency value chains to nature-based adaptation – can influence port development worldwide, creating ripple effects far beyond European borders, from Singapore to San Francisco. As environmental breakdown risks intensify globally, Rotterdam's transformation offers a tested model for resilient, regenerative port systems that prioritise genuine needs, minimise material throughput and operate within the limits of our single, life-sustaining planet.

Figure 1.2 The Port of Rotterdam



Planetary Boundaries Framework: The Earth's Operating Manual

The Planetary Boundaries Framework defines a science-based environmental *safe operating space for humanity*, designed to prevent dangerous, large-scale abrupt or irreversible environmental changes[18], so societies can develop and thrive for generations to come. Developed by an international team of Earth system scientists, it identifies nine critical Earth system processes that regulate the planet's stability and resilience. Breaching these boundaries increases the risk of triggering large-scale, abrupt, or irreversible changes that could undermine the foundations of human well-being.

Each boundary is tracked using key indicators that show how human activity is putting pressure on the planet's life-support systems. Recent assessments reveal that seven of the nine planetary boundaries have now been crossed: climate change, change in biosphere integrity, land system change, freshwater change, modification of biogeochemical flows, ocean acidification, and introduction of novel entities[20].

These boundaries are interconnected. Crossing one boundary affects others and can cause them to exceed safe limits. Maintaining the 'safe operating space' that supports long-term human well-being requires staying within all nine boundaries simultaneously.

Planetary Boundaries[19]

Climate Change
Atmospheric CO_2 concentrations and radiative forcing

Change in Biosphere Integrity
Biodiversity loss and ecosystem function

Land System Change
Conversion of natural ecosystems

Freshwater Change
Alterations of global freshwater use and watershed dynamics

Modification of Biogeochemical Flows
Disruption of nitrogen and phosphorus cycles

Ocean Acidification
Decline in ocean pH due to CO_2 absorption

Increase in Atmospheric Aerosol Loading
Concentration of fine particulate matter

Stratospheric Ozone Depletion
Decline of the protective ozone layer

Introduction of Novel Entities
Synthetic chemical pollution and materials

Figure 1.3 Earth's 2025 Status via the Planetary Boundaries

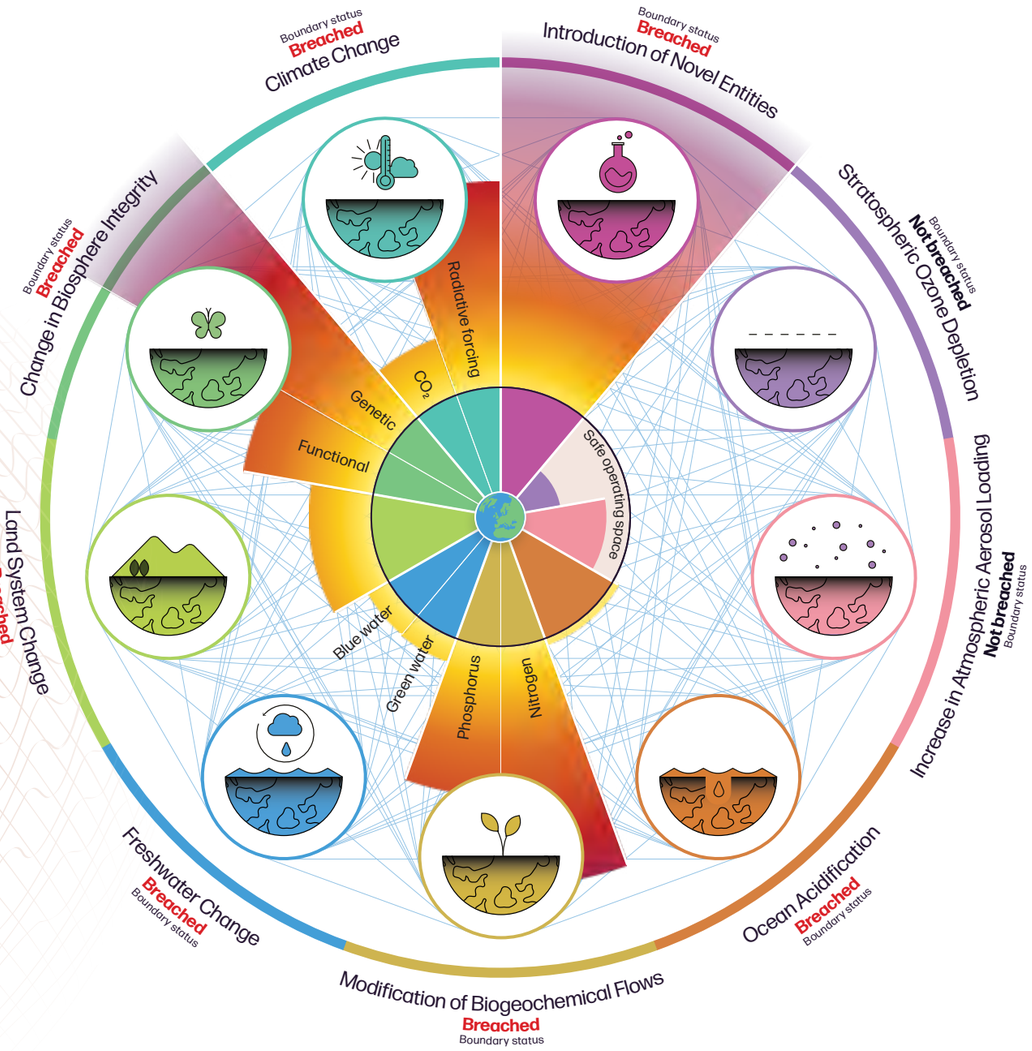
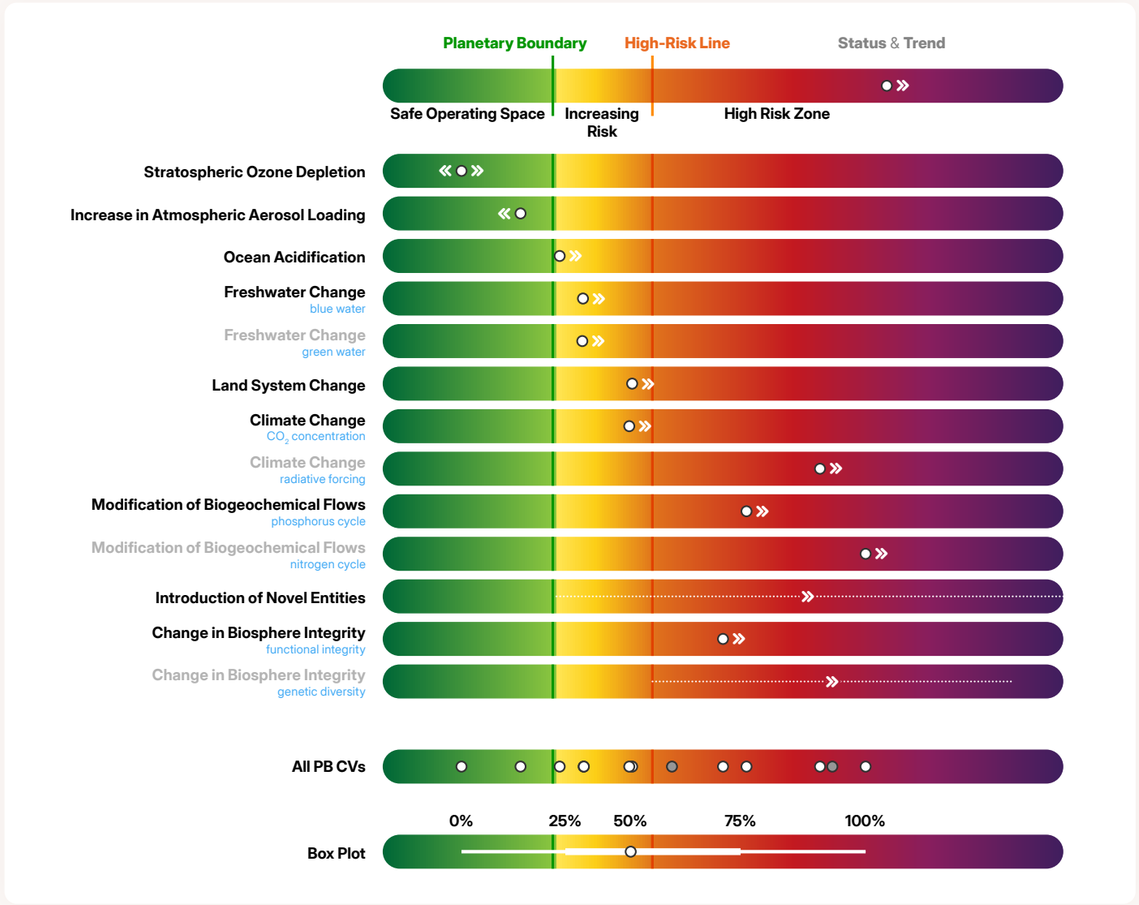
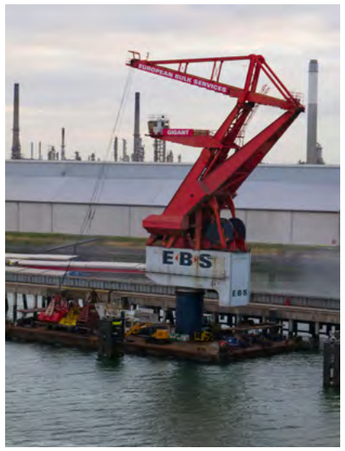


Figure 1.4 Planetary health at a glance.



Just as a blood test provides insights into a human body's health and identifies areas of concern, this Planetary Health Check evaluates the 13 control variables across the 9 Planetary Boundary (PB) processes to report on Earth's stability, resilience, and life-support functions: the overall health of our planet. On the lower colorbar, a classic boxplot summarizes the distribution of all 13 control variable values at once. The boxplot is the dynamic core of the Planetary Health Check symbol and denotes the distribution of all current values of PB control variables with the thin line representing the full range, the thicker line the inner 25 – 75% of control variable values and the dot representing the median of all control variable values. The grey dot denotes uncertainty in the measurement or definition.

Source: *Planetary Healthcheck 2025*. CC BY 4.0.



As the Port of Rotterdam celebrates 750 years of development, this framework offers a forward-looking pathway for the next 750 years, helping to build a regenerative ecosystem supported by resilient infrastructure and sufficiency material throughput.

Why Choose the Planetary Boundaries Framework for Port Transformation?

The Planetary Boundaries Framework offers European policymakers a scientifically robust and systemic foundation for transforming ports in ways that traditional approaches focused on individual issues cannot achieve. It provides a coherent structure for understanding environmental pressures, ensuring that interventions address root causes rather than symptoms while remaining within the planet's ecological limits.

Scientific credibility enhances policy effectiveness: Grounded in the latest Earth system science, the framework defines evidence-based thresholds that can guide legislation, investment and strategic planning. This scientific clarity gives policymakers confidence in setting limits and justifying significant investments in port transformation, both to the public and to relevant industry or government stakeholders.

Interconnected thinking prevents unintended consequences: Because planetary boundaries are interdependent, the framework promotes an integrated approach that considers cascading effects across environmental systems. This whole-system view helps avoid inadvertent harm via well-intentioned actions, such as climate policies that may negatively impact biodiversity or increase chemical pollution.

Provides a unifying framework for policy: The planetary boundaries approach aligns with and strengthens key EU initiatives, including the European Green Deal, Circular Economy Action Plan, and Nature Restoration Law[21]. It provides a shared scientific lens for aligning diverse policy streams, revealing gaps, guiding priority-setting, preventing counterproductive feedback loops, and informing difficult trade-offs. Framing existing measures through this lens helps ensure that Europe's environmental strategies reinforce one another within the planetary boundaries.

Builds on Dutch scientific expertise: Dutch researchers have been working with the Planetary Boundaries Framework for several years. In 2018 the Netherlands Environmental Assessment Agency (PBL) linked[22] the Planetary Boundaries Framework to the UN Sustainable Development Goals (SDGs), translating global quantitative targets to the national scale, and offering direction for policy coherence. Dutch researchers have continued to advance this work, including a 2024 PBL study[23] reimagining how economic activities relate to environmental systems when planetary boundaries become the guiding priority. This intellectual foundation indicates that Dutch policymakers, and decision-makers, are already familiar with planetary boundaries thinking, making the Port of Rotterdam a natural site for implementing this approach.

Leverages innovative Natural Capital Accounting: The Netherlands is also a frontrunner in integrating nature into national decision-making through its pioneering Natural Capital Accounts[24], developed by the Centrale Bureau voor de Statistiek (CBS) with support from the Ministry of Agriculture, Nature and Food Quality (LNV). These accounts go beyond GDP, quantifying how ecosystems contribute to human well-being and how economic activity affects nature. By valuing ecosystem services provided by nature (like carbon storage sinks, water purification, and biodiversity), the Netherlands is embedding ecological limits into economic decision-making, directly reinforcing planetary boundaries principles. This positions the country as a natural choice for advancing planetary boundaries thinking and multi-pronged environmental policy.

Leveraging proven Dutch innovation and resilience: The Netherlands' unique geography and expertise in spatial planning, water management, and climate adaptation provides a strong practical foundation for implementing planetary-boundary-aligned port transformation. As the Port of Rotterdam celebrates 750 years of development, the framework offers a forward-looking pathway for the next 750*, helping to build a regenerative ecosystem supported by resilient infrastructure and sufficiency material throughput. With a national innovative culture of cross-sectoral research and transdisciplinary collaboration[25, 26], the Netherlands is exceptionally positioned to translate planetary science into real-world transformation.

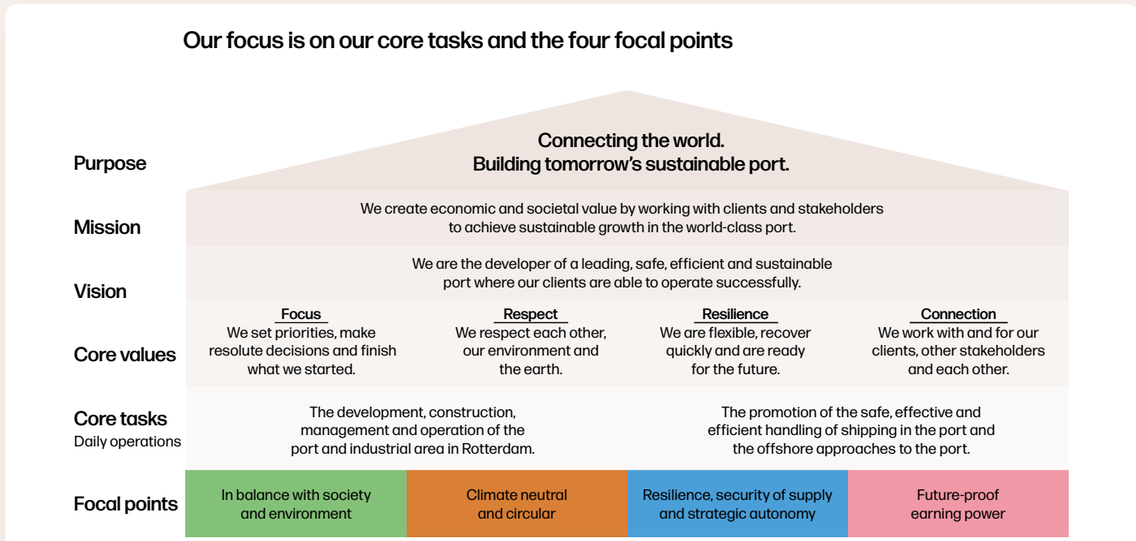
* Rotterdam was founded 755 years ago, in 1270 when a dam was built across the river Rotte. Our vision is for the port-city of Rotterdam to be relevant for at least as long as it has already been in existence.

Document Structure and Intended Audience

This Vision Report is primarily directed towards Rotterdam's port ecosystem and the wider Dutch maritime community, while offering insights relevant to port authorities, policymakers, and sustainability professionals across Europe. Key audiences include:

- The Municipality of Rotterdam
- The Port of Rotterdam Authority leadership and operational teams
- Dutch national and regional policymakers responsible for maritime, environmental, and economic policy
- European port networks seeking evidence-based models for transformation
- Maritime industry stakeholders, including shipping companies, logistics providers, and technology innovators
- Academic and research communities advancing sustainable port development
- Civil society organisations advocating for environmental justice, public health and community resilience

Figure 1.5 Strategic framework overview from the Port of Rotterdam Authority



Source: Port of Rotterdam Authority (2025), *Corporate Strategy 2025-2029*, "Strategic Framework Overview". Not covered by the OPP CC BY licence.

This document is organised around the nine planetary boundaries, each chapter systematically progressing from global science to local implementation. Every boundary section presents the current global status and scientific foundations, examines Netherlands-specific contexts and challenges, analyses direct impacts from shipping and port operations, identifies feasible maritime solutions and interventions, and evaluates current initiatives by the Port of Rotterdam. It concludes with targeted recommendations for both port authorities and policymakers.

This structure builds on a robust scientific foundation while prioritising practical applicability. By moving consistently from global thresholds to national realities and sector-specific impacts and solutions, each chapter equips policymakers with the evidence base needed to grasp both the urgency for action and the pathways for implementation.

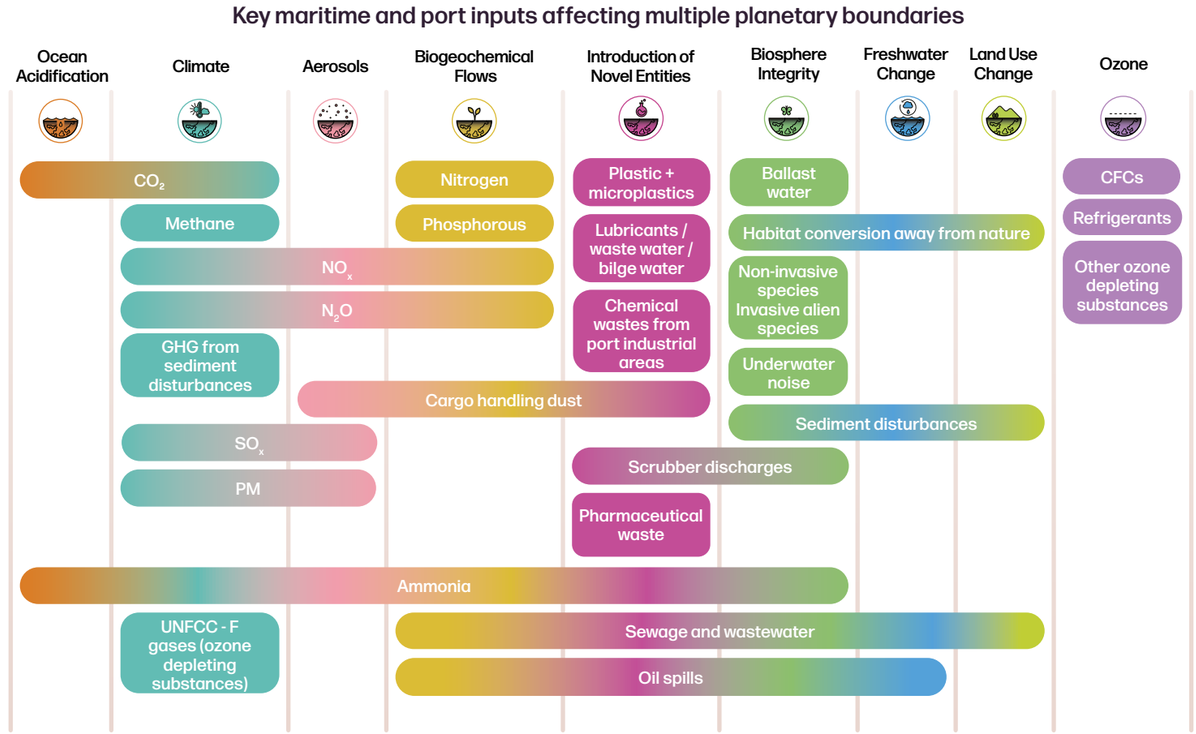
The report concludes with an integrated set of recommendations that synthesise insights across all nine boundaries, culminating in a vision for the Rotterdam port as a flagship *one planet port*. This vision seeks to substantiate a Net Material-Energy Balance Accounting approach, i.e., comprehensive accounting systems that track all material and energy flows associated with port operations, planetary boundaries impacts embedded in value chains, as well as throughput-related impacts, while building on the principles of:

- ***efficiency*** (optimising resource use within planetary limits)
- ***sufficiency*** (meeting genuine needs without excess within planetary limits)
- ***circularity*** (shortening and/or closing resource loops locally to enhance long-term resilience)

Scope and Purpose of this Vision Report

This document provides strategic direction rather than exhaustive regulatory guidance. Our analysis across the nine planetary boundaries establishes a systems-thinking framework for port transformation, deliberately taking a broader perspective than existing regulatory requirements. While mechanisms like the EU Corporate Sustainability Due Diligence Directive (CSDDD), GHG Protocol Corporate Accounting and Reporting Standard, and EU Taxonomy provide important compliance and finance allocation frameworks, our planetary boundaries approach offers integrative thinking that helps identify gaps, synergies, and unintended consequences across multiple environmental systems simultaneously, including throughput impacts.

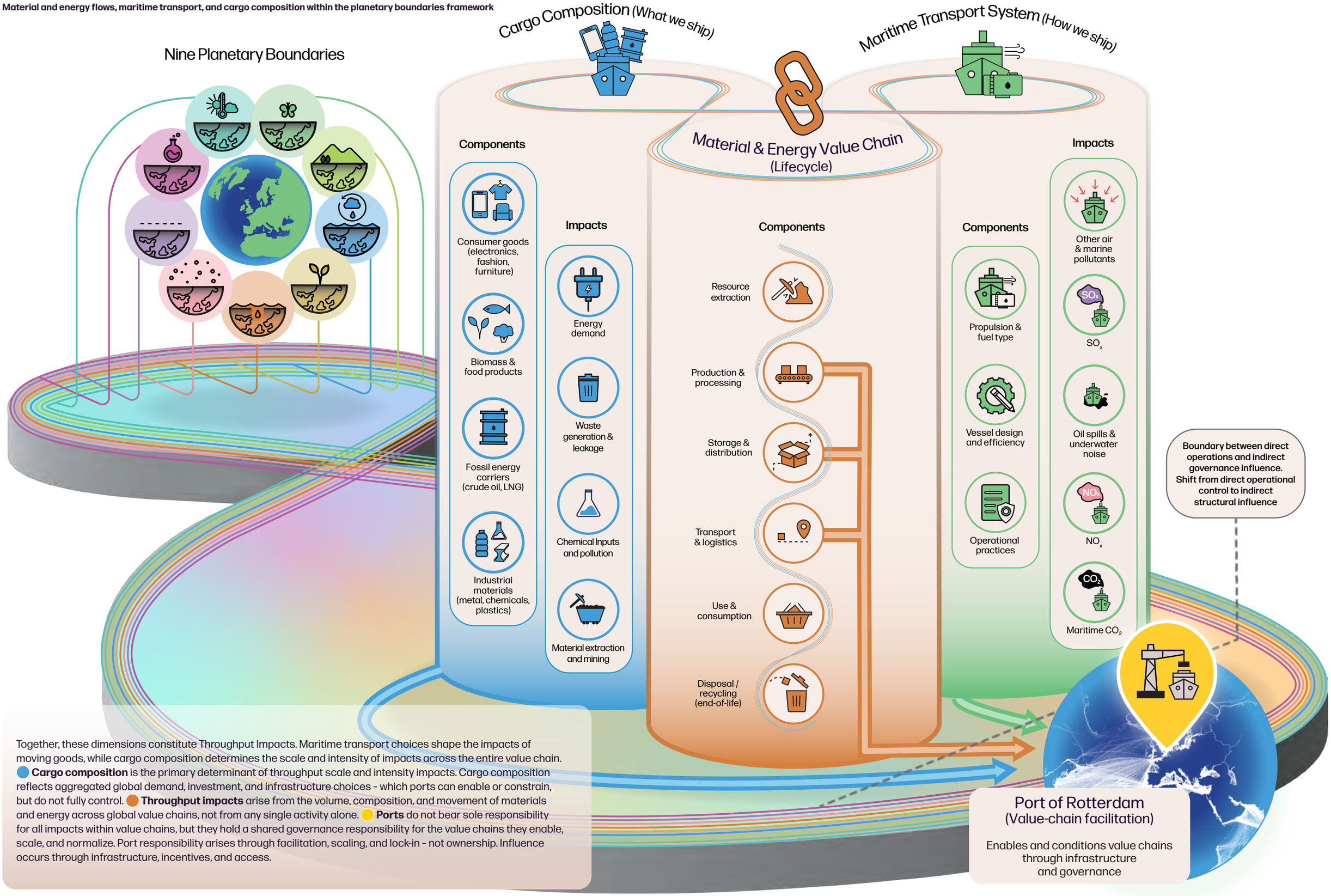
Table 1.1 Cross-boundary pressures from maritime and port activities



Source. One Planet Port Foundation (2026), CC BY 4.0.

Figure 1.6 Throughput Impacts of Global Value Chains Passing Through the Port of Rotterdam

Material and energy flows, maritime transport, and cargo composition within the planetary boundaries framework



Together, these dimensions constitute Throughput Impacts. Maritime transport choices shape the impacts of moving goods, while cargo composition determines the scale and intensity of impacts across the entire value chain. **Cargo composition** is the primary determinant of throughput scale and intensity impacts. Cargo composition reflects aggregated global demand, investment, and infrastructure choices – which ports can enable or constrain, but do not fully control. **Throughput impacts** arise from the volume, composition, and movement of materials and energy across global value chains, not from any single activity alone. **Ports** do not bear sole responsibility for all impacts within value chains, but they hold a shared governance responsibility for the value chains they enable, scale, and normalize. Port responsibility arises through facilitation, scaling, and lock-in – not ownership. Influence occurs through infrastructure, incentives, and access.

Throughput impacts are the full planetary-boundary pressures linked to the materials and products that move through the Port of Rotterdam. They include the embedded impacts of producing those goods (such as raw material extraction, energy use, chemical inputs, land-use change, and waste generation), the supply-chain impacts of transporting them across global value chains (primarily maritime, but also rail, road, and inland waterway transport), and the impacts from their eventual use or disposal (such as emissions from fossil fuel combustion, plastic pollution, nutrient runoff, and end-of-life waste). Looking at throughput impacts shows that port sustainability depends not only on how we ship (fuel, vessel design) but also what we ship (cars, crude oil, metals, plastics, food, fashion, furniture, electronics) and how those value chains drive pressures on planetary boundaries.

We cannot claim comprehensive knowledge of all Rotterdam Port Authority initiatives, many of which may not be publicly documented. Nor can this single document provide detailed implementation roadmaps for every recommendation. Such specificity would require deep-dive collaborations with sector experts, policymakers, and port operators. Rather, this Vision Report serves as a foundation for ongoing dialogue and collaborative development of implementation strategies.

Our intention is to catalyse next-phase work that examines regulatory frameworks in detail, identifies specific gaps and opportunities, and develops practical pathways aligned with both planetary boundaries and existing policy infrastructure. We offer this analysis as an open invitation to researchers, policymakers, industry practitioners and community advocates who wish to contribute knowledge and expertise towards building a regenerative port ecosystem.

Our Call to Action: Move Rapidly from Recognising Urgency to Transforming Systems

We face unprecedented planetary disruption that demands coordinated and decisive responses. Since the 1950s, human activity has accelerated global social, technological, and environmental change at a scale that has fundamentally altered our relationship with Earth's life-support systems. Incremental adjustments can no longer meet the scale of the challenge. This phenomenon, aptly termed the *Great Acceleration*[27], has brought us to a critical turning point. Emerging research shows that health impacts of planetary system changes[28] occur even before boundaries are breached, while crossing them amplifies risks and destabilises societies, with severe consequences for public health[29]. These impacts vary globally[30] and are intertwined across systems, making it difficult to isolate one planetary boundary from another. The cascading and interconnected nature of these disruptions introduces deep uncertainty, translating into social, economic, and security risks. Tackling these risks requires a more adaptive and flexible approach to decision-making and policy development in our rapidly changing world.

Power and influence must be used decisively to build alternative systems that sustain both human and ecological well-being. Protecting planetary boundaries, and thus ensuring humanity's long-term security and survival, demands comprehensive resource mobilisation and a mindset shift. It demands collective courage to move away from the sunk cost fallacy (the tendency to continue investing in a decision or project based on the amount already invested, rather than on future benefits or costs), and the wisdom to invest in regenerative alternatives in a timely manner.

We must take a comprehensive, system-wide approach to reassessing material and energy flows, retain what we consider essential and eliminate the rest. This calls for confronting uncomfortable truths about consumption patterns, transportation intensity, and industrial dependencies that drive planetary boundary overshoot. Our policies and initiatives need to build on the fact that humanity's prosperity is inextricably linked to the planet we inhabit.

This is the moment for transformative action. We invite the Rotterdam Port Authority, policymakers, business leaders, academics and citizens — everyone across sectors, industries and disciplines who shares the ethical commitment to regeneration over extraction, collaboration over competition and long-term value over short-term gain — to join us in building practical, stepwise implementation plans that translate this vision into reality. Together, we can build on Rotterdam's deep expertise in policy, innovation, and logistics, to demonstrate that ports can become epicentres of a regenerative economy, reducing environmental uncertainty, enhancing resilience, and ensuring lasting security. By transforming Rotterdam into a *one planet port* we address root causes, rather than treating symptoms, and secure a thriving future for generations to come.

The journey from conversation to implementation has begun.

Join us in the Rotterdam way: Together we'll make it happen.

Our Vision and Desired Outcomes

Our Vision is Clear: Transform Discourse into Decisive Action.

Too many initiatives remain trapped in endless cycles of consultation and incrementalism while Earth's life-support systems face accelerating degradation — not a gradual decline, but a trajectory towards ecological collapse. This Vision Report represents the One Planet Port Foundation's first step in converting collective intelligence into implementable, stepwise plans that deliver measurable progress towards planetary-boundary alignment for the Port of Rotterdam.

We aim to connect people to the urgency of the situation while offering practical, actionable pathways for hope and agency. Scientific evidence shows that seven of the nine planetary boundaries have already been breached, meaning the Earth is now operating well outside the safe operating conditions that supported stable human development. Addressing this requires immediate, coordinated action at a scale and speed never before achieved.

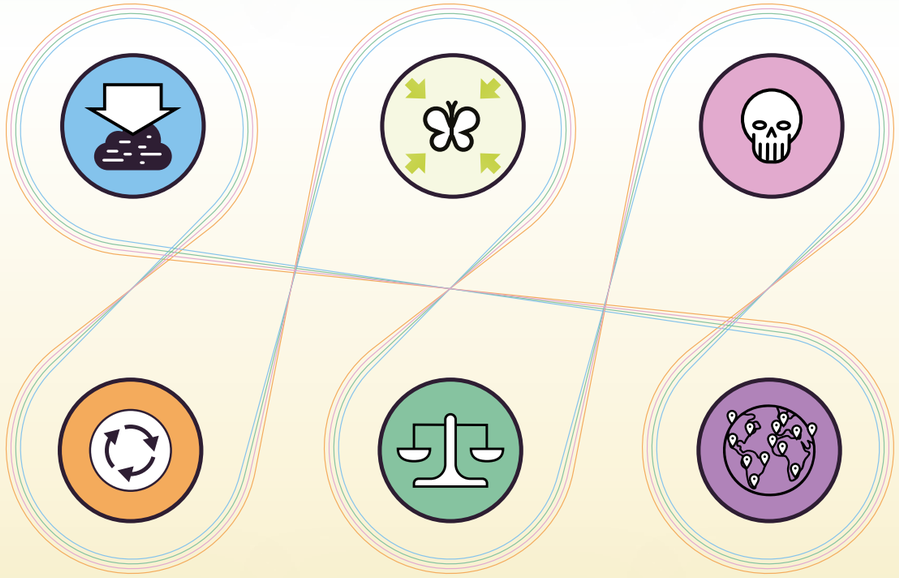
Our desired outcome is system transformation, not incremental improvement. We envision Rotterdam as a regenerative port that actively restores ecological health while maintaining essential economic functions. This means not only changing how the port operates, but what it facilitates, prioritising value chains grounded in material sufficiency, where production and trade meet real societal needs within the planetary boundaries.

This vision includes:

Achieve net-negative emissions across all port operations

Restore biodiversity within port areas and connected ecosystems

Eliminate toxic pollution



Transition to circular material flows within planetary boundaries

Ensure just outcomes for port workers and surrounding communities within planetary boundaries

Demonstrate economic viability that inspires global replication of a net energy-material balance approach, where a solution is only viable if it saves significantly more energy and material than it consumes across its entire lifecycle within planetary boundaries

Achieving this vision requires the port's operations to become fully aligned with ecological limits, not by continuing to facilitate activities that drive environmental breakdown and then offsetting their impacts, but by fundamentally shifting towards enabling activities that, on balance, do no harm.

Finally, true planetary alignment will demand quantifying and transparently addressing ecological impacts along the port-enabled value chains, from extraction to consumption. As a central node in global trade, the Port of Rotterdam holds unique leverage to steer entire supply chains towards sufficiency and sustainability through its policies, incentives, and partnerships. By doing so, it can redefine what it means to be a port in the 21st century: not merely a conduit for commerce but a catalyst for planetary regeneration.

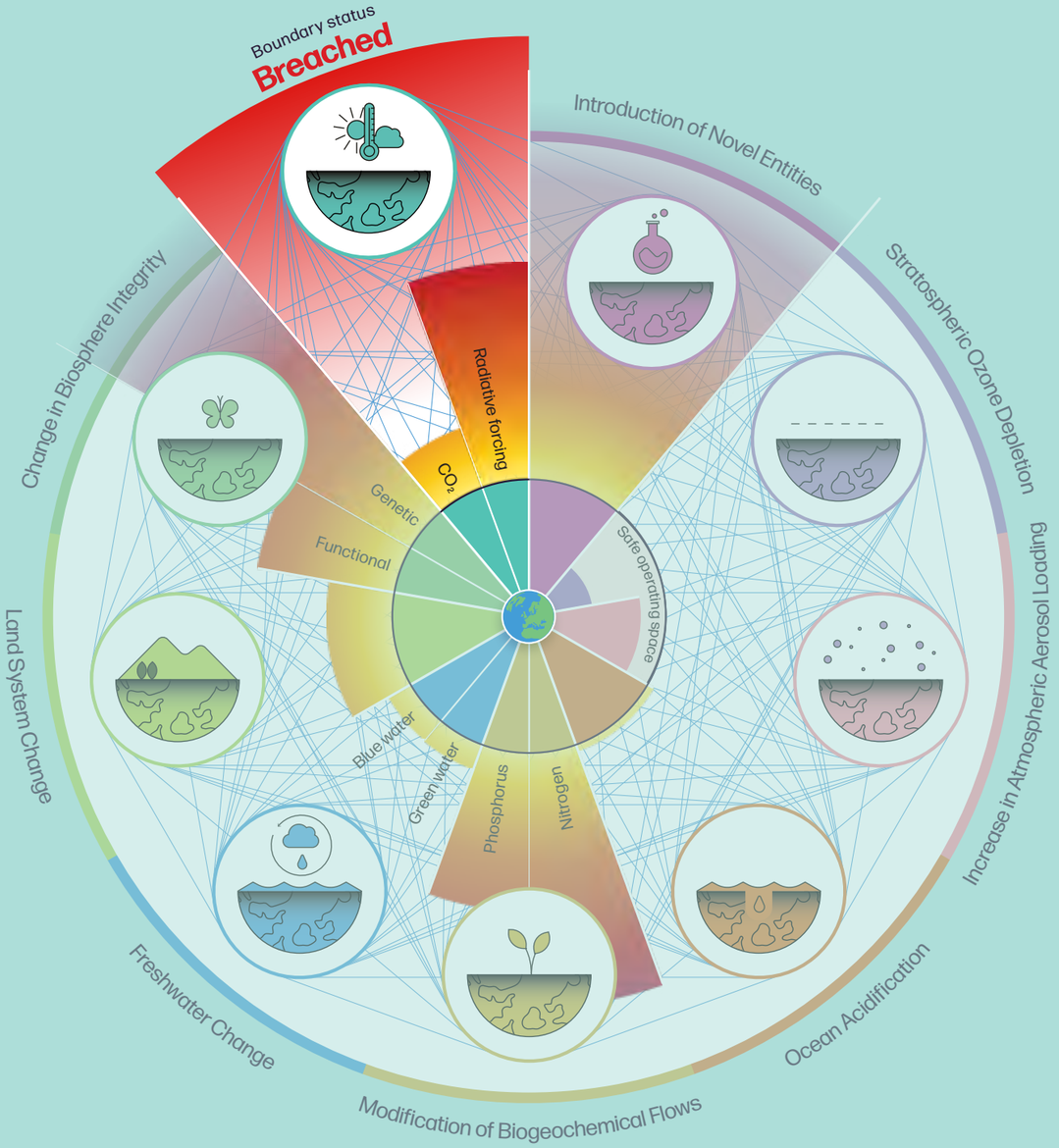
Building on Established Foundations

This Vision Report builds on a strong foundation of existing knowledge, expertise and collaboration. Our scientific advisory network brings together leading researchers across all nine planetary boundary domains, ensuring that every proposed intervention reflects the most current understanding of Earth system science. We have worked to integrate community-based knowledge to capture real-world constraints, opportunities and locally grounded practical solutions. Throughout the report's development, local residents, former port employees, environmental advocates, researchers and business leaders have contributed their experience and perspectives. This has helped to align scientific insight with social and economic realities.

Each planetary boundary section has undergone rigorous expert review, while the overarching framework has been evaluated by systems thinkers and policy specialists to ensure coherence, credibility, and applicability across scales, from global science to local governance.

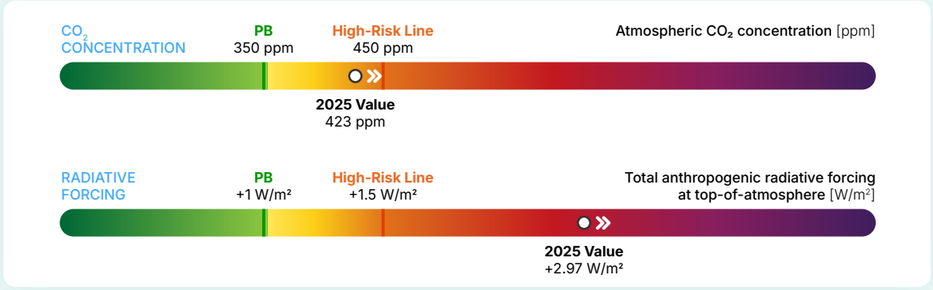
We gratefully acknowledge the contributions of our expert reviewers and community participants, whose insights have deepened and strengthened this work. A full list of contributors is included in the acknowledgements section, with their consent.

CH2 Climate Change



- **CH2 Climate Change**
- **CH3** Change in Biosphere Integrity
- **CH4** Land System Change
- **CH5** Freshwater Change
- **CH6** Modification of Biogeochemical Flows
- **CH7** Ocean Acidification
- **CH8** Increase in Atmospheric Aerosol Loading
- **CH9** Stratospheric Ozone Depletion
- **CH10** Introduction of Novel Entities

Figure 2.1 Planetary Health Check 2025 status: Climate Change



Source. *Planetary Healthcheck 2025*. CC BY 4.0.

Introduction to the Boundary (Global)

Climate change can be defined as the long-term shift in global and regional climate patterns, caused by changes in Earth's energy balance (the difference between incoming energy from the Sun and outgoing heat released back to space). While Earth's energy balance has varied naturally throughout history, the current changes are mainly due to human-driven[31] increases in greenhouse gases. Those gases trap more heat in the atmosphere, raising global temperatures, and disrupting weather patterns[32].

The resultant warming is manifesting in changes across the climate system, including rising surface air and ocean temperatures, altered precipitation patterns, and rising sea levels. Human health, agriculture, water resources, forests, wildlife, and coastal areas are all vulnerable to climate change[33].

Greenhouse gases are released by both natural processes and human activities, but human activities have been the dominant driver of global warming since the mid-20th century. Some gases, such as certain synthetic chemicals are entirely human-made, while others, like carbon dioxide, occur naturally but have reached elevated levels due to human activities. The major sources of greenhouse gases include energy production and transport (through fossil fuel combustion), agriculture, land-use changes, waste management, and industrial processes. Since the 1950s, fossil fuel use has been the largest single source of human-caused emissions[34].

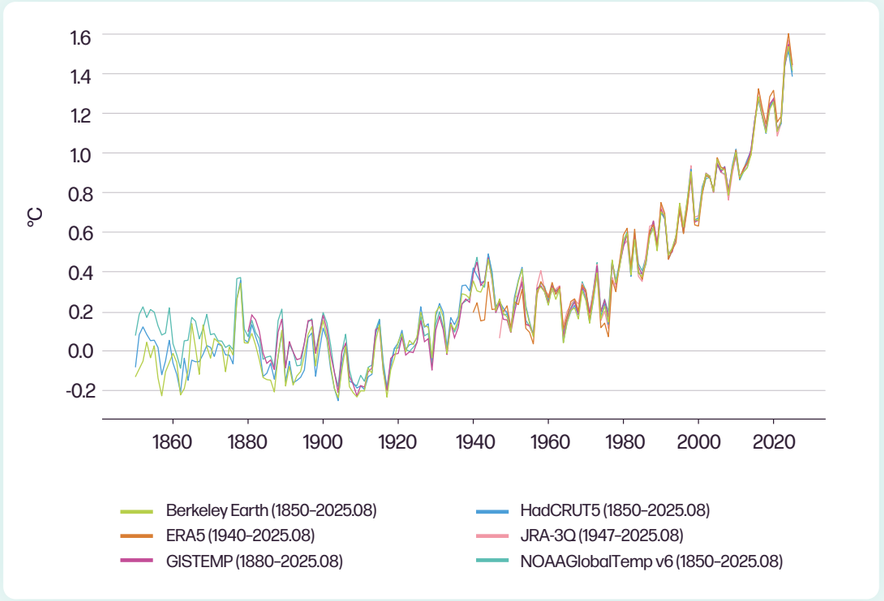
Major greenhouse gases include:

- **Carbon dioxide (CO_2):** The largest contributor to human-caused warming, primarily from burning fossil fuels, deforestation, and other land-use changes.
- **Methane (CH_4)**: Emitted from agriculture (especially livestock), landfills, wetlands, and fossil fuel extraction and transport.
- **Nitrous oxide (N_2O):** Released mainly from agricultural activities (fertiliser use), industry, and fossil fuel combustion.
- **Synthetic chemicals:** Including hydrofluorocarbons (HFCs) and other industrial gases such as perfluorocarbons (PFCs), nitrogen trifluoride (NF_3), and sulfur hexafluoride (SF_6). Many were introduced as replacements for ozone-depleting substances because they do not harm the ozone layer, but they have very high Global Warming Potentials (GWPs) and contribute significantly to climate change.
- **Other substances with important climate effects**: Some substances like **sulphate aerosols** can cool the atmosphere, while **black carbon** (soot) contributes to warming. Water vapour and ozone also affect Earth's energy balance through natural and human-influenced processes.

The Paris Agreement set a target of limiting global warming to no more than 1.5°C above pre-industrial levels. By 2023, the global average temperature had risen to about 1.45°C, already driving extreme weather events and disrupting the lives of millions worldwide[35]. In 2024, indicators of human-induced climate change reached record levels, and it was likely the first calendar year with a global average near-surface temperature exceeding the 1.5°C threshold, estimated at 1.55 ± 0.13 °C above the 1850-1900 average[36]. Early data from 2025 (January – August) shows a global mean temperature of 1.42°C ± 0.12°C above pre-industrial levels, with 2025 projected to be the second or third warmest year on record[37].

The representative indicators to estimate the state of the climate change boundary are **Atmospheric CO_2 Concentration** and **Total Anthropogenic Radiative Forcing at the Top of the Atmosphere (TOA).**

Figure 2.2 Annual global mean temperature anomalies (relative to 1850–1900) from 1850 to 2025 from six dataset



Note. 2025 average is based on data from January-August

Source. World Meteorological Organization (2025), *State of the Climate 2025 Update – COP30*. Used under fair use for reporting and analysis. Not covered by the OPP CC BY licence.

The safe boundary for atmospheric CO_2 concentration is set at 350 ppm[38]. In 2024, the concentration reached **423.9 ppm**, which is 53 percent higher than the pre-industrial level of about 278 ppm in 1750. This means we are significantly beyond the safe threshold. Atmospheric CO_2 concentrations have been rising steadily since industrialisation and are now higher than at any time in the last 15 million years. The increase from 2023 to 2024 was 3.5 ppm, the largest annual increase since modern measurements began in 1957. Over the past decade, the average growth rate has been 2.57 ppm per year, more than triple the rate in the 1960s[39].

While CO_2 is the largest contributor to climate change, other greenhouse gases are also accelerating warming. Global averaged CH_4 concentrations increased from 729 ppb* in pre-industrial times to 1,934 ppb in 2023, a 165% increase. N_2O concentration have increased from 270 ppb in 1750 to 336.9 ppb in 2023, a rise of 24 percent[40]. Concentrations of methane and nitrous oxide– the second and third most important long-lived greenhouse gases—also reached record levels in 2024, at 166% and 25% above pre-industrial levels respectively[41]. Together, the rising levels of CO_2, CH_4, and N_2O are driving unprecedented warming and pushing the climate system further beyond safe limits.

* ppb = parts per billion

Table 2.1 Global GHG emissions by source and decade (decadal averages to 2010s; annual values for 2023-2024)

Units: GT CO_2e	1970 – 1979	1980 – 1989	1990 – 1999	2000 – 2009	2010 – 2019	2014 – 2023	2023	2024 (projection)
GHG	30.9 ± 4.5	34.6 ± 4.6	39.3 ± 5.1	45.1 ± 5.1	52.9 ± 5.4	53.6 ± 5.2	55.4 ± 5.1	
CO_2-FFI	17.3 ± 1.4	20.3 ± 1.6	23.6 ± 1.9	28.9 ± 2.3	35.4 ± 2.8	36.3 ± 2.9	37.8 ± 3.0	38.2 ± 3.0
CO_2-LULUCF	5.2 ± 3.7	5.1 ± 3.6	5.7 ± 4.0	5.2 ± 3.6	4.9 ± 3.4	4.1 ± 2.9	3.6 ± 2.5	4.2 ± 2.8
CH4	6.3 ± 1.9	6.7 ± 2.0	7.2 ± 2.2	7.7 ± 2.3	8.4 ± 2.5	8.7 ± 2.6	9.2 ± 2.7	
N_2O	1.9 ± 1.1	2.2 ± 1.3	2.3 ± 1.4	2.5 ± 1.5	2.7 ± 1.6	2.8 ± 1.7	2.9 ± 1.7	
UNFCCC F-gases	0.2 ± 0.01	0.4 ± 0.1	0.5 ± 0.2	0.8 ± 0.3	1.4 ± 0.4	1.6 ± 0.5	1.9 ± 0.6	

Note. Global anthropogenic greenhouse gas emissions by source and decade following the WGIII assessment. All numbers refer to decadal averages, except for annual estimates in 2023 and 2024. CO_2-equivalent emissions are calculated using GWP100 from AR6 WGI Chap. 7 (Forster et al., 2021). Projections of non-CO_2 GHG emissions in 2024 remain unavailable at the time of publication. Uncertainties are ±8 % for CO_2-FFI, ±70 % for CO_2-LULUCF, ±30 % for CH_4 and F-gases, and ±60 % for N_2O, corresponding to a 90 % confidence interval. "GHG" in row one is the sum of the other rows.

Source. Forster et al. (2024), *Indicators of Global Climate Change 2024: Annual update of key indicators of the state of the climate system and human influence.* Earth System Science Data. Licensed under CC BY 4.0.

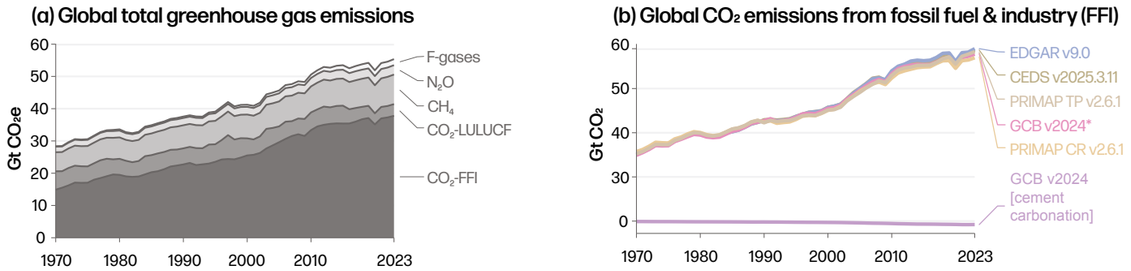
The rising concentrations of CO_2, CH_4, and N_2O are part of a broader picture of human-driven changes to Earth's energy balance, known as anthropogenic radiative forcing. Net radiative forcing sums up all the ways human activities impact the global climate and force the natural balance of the planet's energy system. This includes the emissions of greenhouse gases, aerosols, and land-use changes. It is a key measure of how much additional heat energy is added to the Earth system, representing the overall strength of human-induced climate change[42]. Radiative forcing is expressed in watts per square metre (W/m^2). The safe boundary for radiative forcing is set at +1.0 W/m^2 [43], yet by 2024, observations show it had reached 2.97 W/m^2 relative to pre-industrial levels (1750)[44], nearly three times the safe threshold. As long as this forcing persists, global temperatures will continue to rise.

The consequences of failing to address climate change are severe and far reaching:

- **Cascading tipping points collapse:** Climate tipping points are critical components of Earth's natural systems that can abruptly shift into a new state, which causes the climate system to change irreversibly. They may appear stable as temperatures rise, but once a certain threshold is crossed, even tiny changes can push them over the edge into dangerous condition that's very hard to reverse[45]. Crossing one tipping point can trigger others, unleashing a domino-effect chain reaction that makes some regions far less able to support human and natural systems. Unexpected and extreme events will become routine and drastically altered rainfall patterns common, undermining mitigation and adaptation efforts. Supply chain breakdown, overlapping health crises and deep economic instability are also likely to follow.

- **Coral reef die-off:** The world has already crossed its first tipping point: warm-water coral reefs are experiencing widespread die-off, with over 80% affected by the worst mass bleaching event on record since 2023[46]. As global warming approaches 1.5°C, multiple additional tipping points are at risk of being crossed, including the Amazon rainforest (threatened by widespread dieback below 2°C) and the Atlantic Meridional Overturning Circulation, i.e., AMOC (at risk of collapse below 2°C, which would radically undermine global food and water security and plunge northwest Europe into severe winters)[47]. Current national climate commitments are insufficient to prevent these tipping points, as they commit the world to warming likely exceeding 2°C before 2100[48].

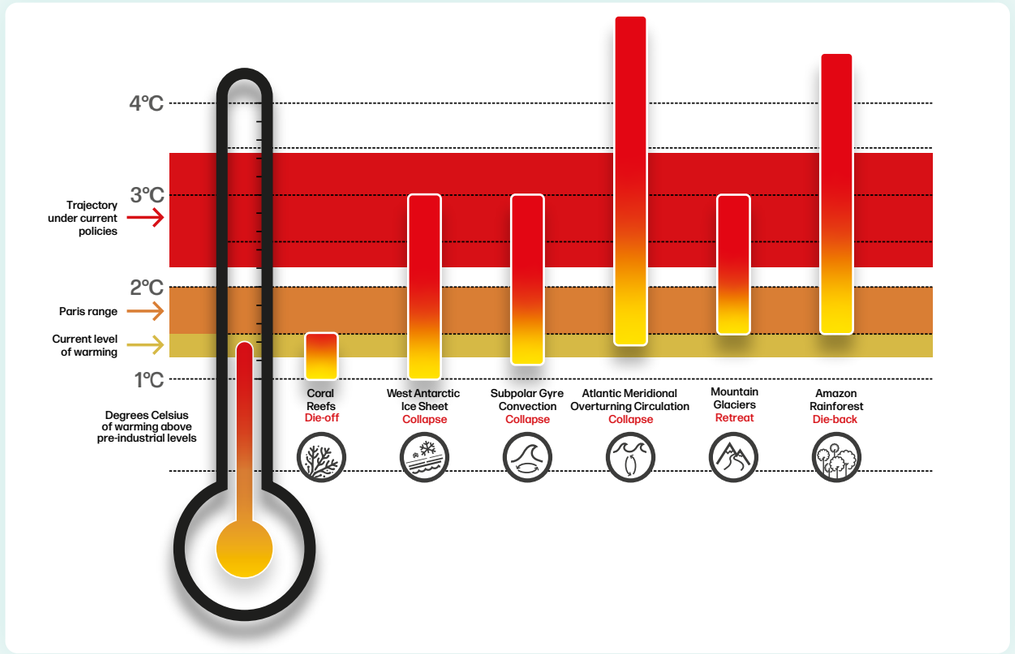
Figure 2.3 Annual global anthropogenic greenhouse gas emissions by source (1970–2023)



Note. Emissions from fossil fuels and industry (CO_2-FFI); net CO_2 emissions from land use, land-use change and forestry (CO_2-LULUCF); CH_4 emissions; N_2O emissions; and fluorinated gas (F-gas) emissions comprising hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF6) and nitrogen trifluoride (NF_3) - hereafter the "UNFCCC F-gases."

Source. Earth System Science Data (2025), *Global Carbon Budget 2024 update*, CC BY 4.0.

Figure 2.4 Increasing risks of Earth system tipping points with rising global temperatures



Source. Global Tipping Points Report (2025), *Global Tipping Points* 2025, CC BY 4.0.

- **Ecosystem destruction and biodiversity collapse:** Mass species extinction erodes ecosystem resilience, eliminates natural medicines, and triggers unpredictable ecological cascades that undermine agriculture and human health. Large-scale ecosystems such as coral reefs, the Amazon rainforest, and boreal forests are rapidly approaching critical thresholds. Once these systems collapse, they shift from absorbing carbon to releasing it, accelerating warming and eliminating crucial life-support services[49]. Degradation of the Amazon alone could release up to 75 Gt of CO_2, adding 0.1 – 0.2°C[50] of warming and risking 10% of the planet's biodiversity[51]. Coral reefs are projected to decline by 70-90% at around 1.5°C of warming[52], threatening food security and the livelihoods for millions of people who depend on marine ecosystems. WWF's *Living Planet Report 2024* warns of a catastrophic 73% decline in the average size of monitored wildlife populations between 1970 and 2020, a collapse that leaves ecosystems less resilient, more vulnerable to climate change, and leading to regional tipping points with global consequences[53].

- **Global food system collapse:** Climate change is destabilising agricultural productivity through shifting rainfall patterns, extreme weather events, and ecosystem breakdown. Monsoon systems that feed billions are weakening, while rising temperatures are rending vast agricultural regions unsuitable for current crops. Maize yields are projected to fall by 24% by late century, with declines becoming apparent by 2030, while wheat yields may rise by about 17%, changes with severe global consequences[54]. Ocean warming and acidification devastate fisheries, threatening the primary protein source for over a billion people[55]. Fish provides at least one-fifth of the animal protein for over 3 billion people worldwide[56]. Climate-driven migration from failing agricultural regions can trigger food price spikes and social unrest[57]. The combination of crop failures, fisheries collapse, and supply chain disruption threatens food security even in developed nations. A study by the European Central Bank and the Barcelona Supercomputing Centre linked recent price surges directly to climate change, including a 300% spike in Australian lettuce, a 50% increase in European olive oil, and an 80% rise in US vegetable prices[58].

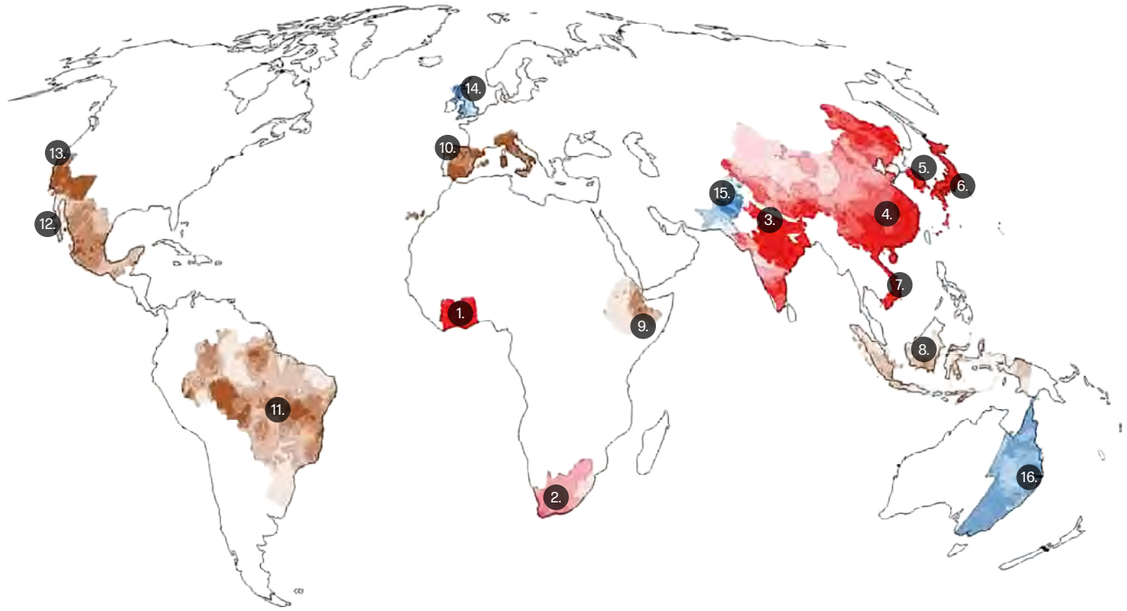
Climate change linked price surges:

300%
price spike in Australian lettuce

50%
price increase in European olive oil

80%
rise in US vegetable prices

Figure 2.5 Climate-related extreme events linked to recent food price spikes (2022-2024)



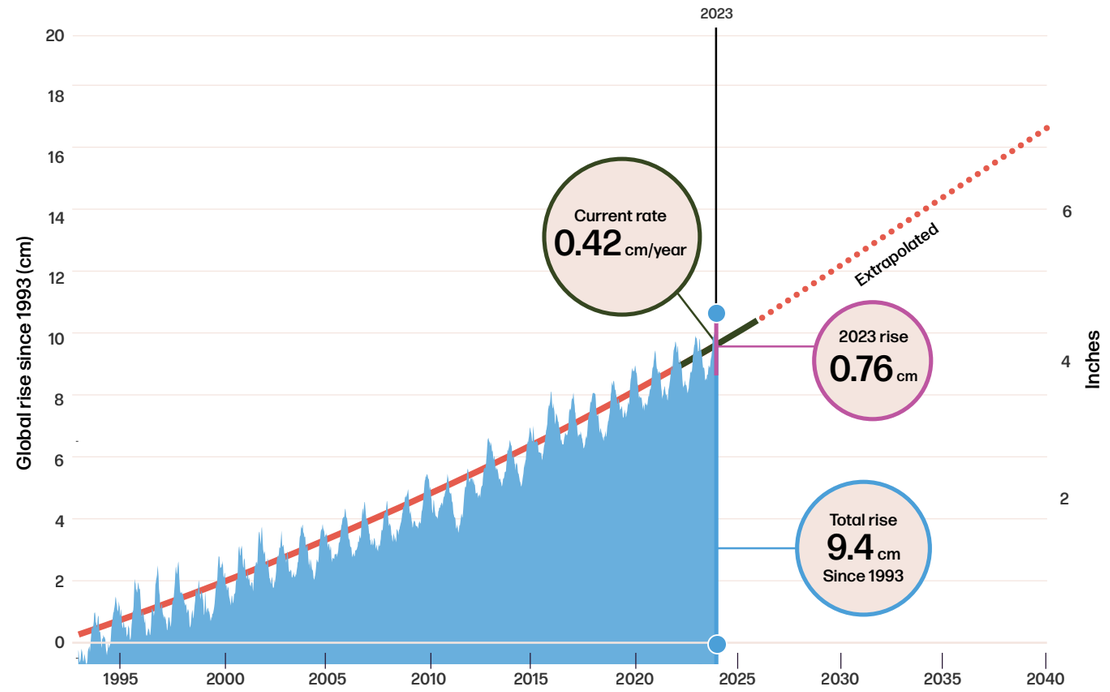
1. **Ghana/Ivory Coast:** global cocoa prices 280% higher in April 2024 after Feb heatwave
2. **South Africa:** maize prices 36% higher in April 2024 following March heatwave
3. **India:** onion/potato prices increase 89/81% in 2nd quarter of 2024 after May heatwave
4. **China:** vegetable prices rise 30% from June to August 2024 following August heatwave
5. **South Korea:** cabbage prices 70% higher in Sept 2024 after August heatwave
6. **Japan:** rice prices 48% higher in September 2024 after August heatwave
7. **Vietnam:** Robusta coffee prices 100% higher in July 2024 after Feb heatwave
8. **Indonesia:** rice prices 16% higher in Feb 2024 after 2023 drought
9. **Ethiopia:** food prices 40% higher in March 2023 following 2022 drought
10. **Italy/Spain:** olive oil prices 50% higher in EU in January 2024 after 2022/23 drought
11. **Brazil:** coffee prices 55% higher in August 2024 after 2023 drought
12. **Mexico:** fruit and vegetable prices 20% higher in Jan 2024 following 2023 droughts
13. **California/Arizona:** vegetable prices 80% higher in US in Nov 2022 after western droughts
14. **UK:** potato prices increase 22% from Jan to Feb 2024 following wet winter
15. **Pakistan:** 50% increase in rural food prices in weeks following August 2022 floods
16. **Australia:** price of lettuce increases 300% in June 2022 following spring floods

Note. Map highlights documented cases where food price increases were reported following extreme heat, drought, or flood conditions since 2022. Colours represent exceedance of historical temperature and precipitation percentiles.

Source. Environmental Research Letters (2023), *Climate extremes, food price spikes, and their wider societal risks*, CC BY 4.0.

- **Accelerated sea level rise:** Sea level rise has two main drivers: the melting of ice sheets and mountain glaciers, and the expansion of warming oceans[59]. NASA data reveals the rate of global sea level rise has more than doubled, increasing from 0.18 cm per year in 1993 to 0.42 cm per year in 2023. Since 1993, this acceleration has added about 9.4 cm to the global average sea level[60]. Scientists estimate that current rates of acceleration mean that we are on track to add another 20 cm of global mean sea level by 2050[61]. The projected rise over the next three decades will double the amount of change seen in the previous century, greatly increasing the frequency and severity of coastal flooding worldwide[62]. Around 230 million people currently live within 1 metre of present-day sea level, and 1 billion live within 10 metres[63]. Without adaptation efforts, annual flood damages for the world's 136 largest coastal cities could reach $60-63 billion by 2050, and potentially exceed $1 trillion per year in the longer term if protection systems are not upgraded[64, 65].

Figure 2.6 Satellite-based global mean sea level rise since 1993



Note. Graphic shows global mean sea level measured by satellite altimetry since 1993. Solid red line indicates observed rise; dotted line shows projected rise. 2023 spike reflects El Niño influence. Credit in original figure: NASA-JPL/Caltech.

Source. NASA-JPL/Caltech (2024), *Satellite Record of Sea Level Rise.* Retrieved from NASA Sea Level Change portal.

- **Systemic economic and financial risk:** Climate impacts create uninsurable risks that exceed the capacity of financial markets to manage[66]. As insurance becomes unavailable for coastal properties, agriculture, and climate-exposed infrastructure, investment and mortgage markets freeze, undermining economic stability. The exponential increase in extreme weather events and simultaneous climate shocks across multiple sectors trigger systemic instability that traditional economic models cannot predict or contain. Reported disaster losses from extreme weather have increased 600% since the 1970s[67]. According to the World Economic Forum, the costs of damage from extreme weather linked to human-driven climate change have nearly tripled since 2000, rising from $149 billion between 2000 and 2004 to a projected $435 billion for 2020-2024[68]. Without adaptation measures (actions taken to prepare for, reduce, or cope with the negative impacts of climate change), the physical risks caused by a global temperature rise of 2.7°C could see the world's largest companies incur total annual costs of $1.2 trillion by 2050, according to S&P Global[69]. The European Central Bank warns that droughts in the Eurozone could erase 15% of economic output and put loans (e.g., corporate, household, and agricultural loans) worth €1.3 trillion at risk[70].

- **Loss of human life and mass migration:** A 2023 study assessing 185 extreme weather events from 2000 to 2019 estimated that a net of 60,951 deaths during this period are attributable to climate change[71]. The economic value assigned to these climate change–related deaths is estimated at $431.8 billion to date. The same study attributed 53% of the total economic damages from the 185 events, amounting to $260.8 billion, to climate change[72]. Between 2008 and 2016, weather-related disasters such as storms, floods, wildfires, and droughts forcibly displaced an average of 21.5 million people each year[73], with displacements reaching a record 32.6 million in 2022[74]. Looking ahead, the World Bank projects that deteriorating agricultural conditions and declining water availability could force up to 86 million additional people to migrate within sub-Saharan Africa, 40 million in South Asia, and 17 million in Latin America, a total of 143 million climate migrants by 2050[75].

Climate change is inextricably linked to other planetary boundaries, and action, or inaction, can have far reaching consequences:

Ocean Acidification: Atmospheric CO_2 concentration is the key control variable for the ocean acidification boundary. Often called the "evil twin" of climate change[76], ocean acidification is occurring about 100 times faster than any natural change in the past 650,000 years, showing that human activities are transforming ocean chemistry at unprecedented speed[77].

Biosphere Integrity: Research on more than 130,000 species projects that even at 1.5°C of warming, extinction levels (median 9%) would be about 1,000 times higher than natural background rates. At 3.2°C warming, nearly half of all insects (49%) and plants (44%) would lose more than 50% of their geographic range[78].

Land System Change: Deforestation and land use change reduce carbon storage capacity and increase greenhouse gas emissions, while climate change exacerbates desertification and drives ecosystem shifts. Large-scale events such as permafrost thawing or the mass dieback of the Amazon or boreal forests would release vast amounts of stored carbon, accelerating warming, and fuelling dangerous feedback loops[79].

Modification of Biogeochemical Flows: Climate change alters rainfall and temperature patterns, disrupting global nutrient cycles. Nitrous oxide, a potent greenhouse gas, is released through agricultural processes (especially fertiliser use), fossil fuel combustion, and industrial processes. Increased N_2O emissions accelerate climate change, which in turn can trigger further nitrogen releases from soils and ecosystems, creating feedback loops that accelerate both climate change and ecosystem disruption.

Freshwater Change: Climate change alters rainfall patterns, causing more severe droughts and storms, undermining the availability of safe, renewable freshwater. A quarter of the world's population now faces extreme water stress, where more than 80% of the available supply is withdrawn each year[80], leaving little to buffer against droughts, support ecosystems, or meet future demand.

National Context: The Netherlands

The Dutch Climate Law (Klimaatakkoord[81]) was adopted in 2019 and amended in 2023 to align it with the European Climate Law. It sets targets for climate neutrality by 2050 and a CO_2-free electricity sector by 2035, and a 55% reduction of net greenhouse gas (GHG) emissions by 2030 compared to 1990 levels. To ensure the 2030 target is met, the Netherlands has adopted an 'over-programming' of measures, aiming instead for a 60% emissions reduction by 2030[82]. The country's long-term strategy for 2050, however, still dates from 2019[83] and is still based on the earlier Klimaatakkoord targets.

In 2023, Dutch GHG emissions fell by 6.8%, driven by reduced coal and gas use in electricity generation and an increase in renewable energy adoption[84]. Renewables accounted for 17% of total energy consumption, up from 15% in 2022. Overall emissions have dropped 35.6% since 1990[85].

However, the latest Climate and Energy Outlook (KEV 2025)[86], from the Netherlands Environmental Assessment Agency, warns that reaching the 2030 climate goal is now extremely unlikely. With current implemented policy, the country is on track for only 45-53% emissions reduction by 2030, with additional calculable plans bringing this to 47% to just below 55%. This means that the 55% target lies outside the confidence interval with less than 5% probability of achievement. To reach the target with 50% certainty requires an additional 13 megatonnes CO_2-equivalent reduction by 2030; with 95% certainty, 22 megatonnes. The Netherlands is also not on track to meet legally binding European goals for renewable energy. Projections show 29-36% renewable energy by 2030, falling short of the 39% target[87].

Key factors undermining progress include delays in offshore wind deployment (reduced from 12 GW to 10 GW expected capacity by 2030), potential termination of the crucial SDE++ subsidy scheme for sustainable technologies after 2027, and political uncertainty around carbon taxation for industry which is undermining investments[88].

Table 2.2 Greenhouse gas emissions of the Netherlands by gas (1990–2023)

	CO_2 incl. indirect and LULUCF	CH_4 incl. LULUCF	N_2O incl. LULUCF	HFCs	PFCs	SF_6	Total (incl LULUCF)
1990	167.7	36.5	16.1	4.7	2.4	0.2	227.5
1995	177.7	34.0	16.2	6.3	2.1	0.3	236.5
2000	176.5	27.9	14.4	4.0	1.7	0.2	224.6
2005	182.5	22.9	12.9	1.3	0.3	0.2	220.1
2010	186.8	22.3	7.9	2.0	0.3	0.1	219.4
2015	169.0	20.9	8.1	1.7	0.1	0.1	200.0
2020	140.0	19.5	7.5	1.0	0.1	0.1	168.3
2020	130.8	18.6	6.7	0.8	0.1	0.1	157.0
2023	120.6	18.4	6.6	0.7	0.0	0.1	146.4

Note. LULUCF = land use, land-use change, and forestry. Values in Tg CO_2e; differences due to rounding in original table.

Source. RIVM (2025), *Emissions trends per gas*, 1990-2023, RIVM Report 2025-0005, p. 18. Not covered by the OPP CC BY licence.

According to a 2024 update from the EU's Emissions Database for Global Atmospheric Research (EDGAR)[89], the Netherlands accounted for 0.28% of global GHG emissions.

Table 2.3 Greenhouse gas emissions of the Netherlands from the EDGAR database (1990–2023)

1990	2000	2005	2015	2020	2022	2023	2023 World Total
223.19	225.07	221.35	201.01	170.50	161.17	150.75	0.28%

Note. Values in Mt CO_2e; "2023 %" indicates share of global emissions.

Source. European Commission Joint Research Centre (2024), *EDGAR v7.0 Global Greenhouse Gas Emissions Database.* Country Profile: Netherlands. Not covered by the OPP CC BY licence.

Differences between EDGAR and the Netherlands' National Institute for Public Health and the Environment (RIVM) data reflect distinct methodological approaches: RIVM produces the official national reporting using detailed country-specific data and methods required under UNFCCC obligations, while EDGAR provides independent, globally standardised estimates for international comparisons and scientific analysis. Including both datasets offers a fuller picture; RIVM data serves as the Netherlands' official baseline for climate policy, whereas EDGAR data allows benchmarking against other maritime nations.

Methodological variations at global, country and industry levels, including the pollutants covered, assumptions applied, and modelling approaches, mean that these datasets are complementary rather than directly comparable. Achieving consistent methodologies and integrating the latest data are essential for accurately measuring the impact of different policy or technological interventions.

In the 2025 Climate Change Performance Index, the Netherlands (NL) ranks fifth globally[90], behind Denmark and ahead of the UK[91*]. NL scores high on renewable energy and GHG emissions reduction, medium on climate policy, but low on energy use due to high overall consumption. While the coalition government under Prime Minister Dick Schoof continued many previous climate measures, experts warn of weaker implementation and reduced support for solar energy[92].

The Netherlands has the highest per capita installed solar capacity in Europe but faces grid infrastructure bottlenecks that hinder the pace of renewable expansion. The country maintains a €3.2 billion annual renewable energy stimulus, has committed to phasing out coal by 2030, and closed the major Groningen gas field in 2024. However, it continues to struggle with high agricultural emissions, weak implementation of EU nitrogen targets, and uncertainty over ambitious 2040 climate commitments under the current government[93].

In the October 2025 elections, the centrist liberal D66 party narrowly won with 26 seats (leading by 29,668 votes over the far-right PVV, which also won 26 seats)[94], marking D66's strongest-ever performance. Coalition formation talks are ongoing, with D66 and the Christian Democrats (CDA) currently tasked with drafting a coalition framework, focusing first on breakthrough solutions for nitrogen pollution and energy infrastructure, followed by housing, migration and security[95]. The outcome will determine whether the Netherlands maintains ambitious climate action, as D66 campaigned on green energy and housing solutions, with emphasis on affordability and energy independence[96].

Public awareness of climate change is high among the Dutch. A 2023 survey found that 80% of Dutch respondents rated the seriousness of climate change between 7 and 10 on a 10-point scale, and 72% reported taking personal action within the past six months to address it[97]. Most respondents (66%) felt the national government was not doing enough, a 5% reduction from the 2021 survey, when 71% held that view. A strong majority also agreed that tackling climate change should be a public health priority and that the costs of the damages due to climate change are much higher than the costs of the investments needed for a green transition.

* The Climate Change Performance Index (CCPI), published annually since 2005, is an independent monitoring tool for tracking countries' climate mitigation performance. Results are compiled with the aid of 450 national experts evaluating their countries' most recent national and international climate policies. *https://ccpi.org/ccpi-philosophy-team/*

The future climate scenarios series[98], developed by the Royal Netherlands Meteorological Institute (KNMI), translates the latest IPCC findings into projections specific to the Netherlands. These scenarios help policymakers and stakeholders anticipate and adapt to rising temperatures, accelerating sea level rise, and shifting rainfall patterns.

The below summary table provides an overview of the different scenarios from KNMI and the related impacts on people and infrastructure.

Table 2.4 Summary of KNMI climate scenarios and associated impacts based on IPCC AR6

Metric/Scenario	Low Emissions (SSP1-2.6)	Moderate Emissions (SSP2-4.5)	High Emissions (SSP5-8.5)
SSP Scenario Description (IPCC AR6)	**Sustainable Development**: The world shifts towards a more sustainable path, with an emphasis on inclusive development, reduced inequality, and lower resource and energy intensity. Global CO_2 emissions are strongly reduced, reaching zero after 2050.	**Middle of the Road:** Social, economic, and technological trends follow historical patterns with slow progress towards sustainability. Development and income growth proceed unevenly. CO_2 emissions hover around current levels before declining by mid-century but do not reach net-zero by 2100.	**Fossil-Fueled Development:** Rapid economic growth driven by intensive fossil fuel use and energy-intensive lifestyles. Global markets are integrated, leading to technological progress. CO_2 emissions almost double by 2050. This represents a "worst-case scenario" with very high greenhouse gas emissions.
Global Warming by 2100 (relative to pre-industrial, 50% likelihood) (IPCC AR6)	1.7°C	2.8°C	4.9°C
Dutch Annual Mean Temperature Increase by 2100 (relative to 1991-2020) (KNMI 2023)	0.9°C (Wet & Dry)	2.0°C (Wet & Dry)	4.1°C (Wet) / 4.4°C (Dry)
Likely Impacts (IPCC AR6, scientific literature)	Milder winters, more frequent warm days (above 25°C), earlier blooming seasons. Moderate increase in heat-related discomfort, some stress on vulnerable groups during heatwaves.	Noticeably warmer summers with increased frequency and intensity of heatwaves (e.g., more "tropical days" above 30°C). Increased health risks for vulnerable populations, more heat-related mortality, disrupted sleep, reduced concentration. Earlier and longer pollen seasons. Higher demand for cooling energy.	Significantly hotter summers with more extreme and prolonged heatwaves, potentially exceeding 40°C on extremely hot days across much of the country. Severe health impacts, significantly increased mortality, and widespread discomfort. Higher risk of summer smog. Shift in plant and tree species (e.g., from France) leading to new allergens.
Precipitation (General Trends) (KNMI23)	Wetter winters, moderate summer drying (Wet); Moderate winter wetting, strong summer drying (Dry).	Winter wetting, moderate summer drying (Wet); Moderate winter wetting, strong summer drying (Dry). Increased probability of drought periods and severe summer downpours.	Stronger winter wetting and more extreme summer drying. Substantially increased precipitation deficit, especially in the south, leading to more frequent and severe droughts. Higher intensity of extreme summer downpours (flash floods). Increased salinization of surface waters, impacting agriculture and freshwater supply.

Table 2.4 (continued)

Metric/Scenario	Low Emissions (SSP1-2.6)	Moderate Emissions (SSP2-4.5)	High Emissions (SSP5-8.5)
Sea Level Rise at Dutch Coast by 2100 (relative to 1995-2014) (KNMI23)	Likely range: 0.3-0.5 meters	Likely range: 0.5-0.8 meters	Likely range: 0.8-1.2 meters, with a low confidence chance of approaching 2 meters due to potential rapid ice sheet melt.
Possible Major Impacts on Dutch Infrastructure, Economy, and Health (IPCC AR6, scientific literature)	Continued need for investments in water management (dikes, sand nourishment) to adapt to gradual sea level rise. Minor impacts on infrastructure and health. Some financial risks from extreme weather, but manageable.	Increased flood risk for low-lying areas, requiring significant upgrades to dikes and flood defences. Greater stress on electricity grids due to increased cooling demand during heatwaves. Agricultural impacts from both drought and intense rainfall. Financial risks for businesses and banks due to physical climate risks (e.g., property damage, loan defaults). Increased heat-related illnesses and mortality. Potential spread of vector-borne diseases.	Catastrophic increases in flood risk due to substantial sea level rise and extreme precipitation, potentially overwhelming current defences and requiring major spatial adaptations. Severe strain on critical infrastructure (energy, IT, transport). Significant economic costs from damages, adaptation measures, and reduced labour productivity due to heat. Major public health crisis due to widespread heat stress, respiratory issues from smog and pollen, and increased infectious diseases (e.g., Legionnaires' disease, Lyme disease). Severe mental health impacts (eco-anxiety).

Note. SSP scenario descriptions are summarized from IPCC AR6. Dutch projections are based on KNMI'23. Impact descriptions synthesize IPCC AR6 WG I/II and other scientific literature.

Source. One Planet Port Foundation (2026), based on *KNMI (2023) climate scenarios* and IPCC AR6 Working Group I and II assessments. Not covered by the OPP CC BY licence where third-party data apply.

The Dutch Port and Maritime Cluster[99]

In 2022, the Dutch maritime cluster, covering activities such as shipbuilding, shipping, and maritime services, generated €95.2 billion in turnover and €31.1 billion in total added value (€25.9 billion direct, €5.2 billion indirect), representing 3.2% of national GDP. The sector employed 305,765 people, of whom 201,914 were in direct jobs, accounting for 3.0% of the total employment in the Netherlands. Overall maritime employment grew by 6.0% compared with 2021. Maritime exports reached €59.5 billion, 8.1% of total Dutch exports, up from €52.0 billion the previous year.

When the maritime cluster is combined with the Dutch port cluster, which includes port operations, cargo handling, logistics, and related services, the total economic contribution rises to €72.4 billion in total added value (€50.4 billion direct) in 2022, equal to 7.5% to GDP including indirect effects. Together these combined port clusters provided 575,490 total jobs, of which 303,960 were direct, representing 5.7% of national employment.

The Maritime Master Plan

The Netherlands' Maritime Masterplan received €210 million[100] from the National Growth Fund (allocated in 2023, finalised in 2024) to develop 40 climate-neutral demonstration ships across four strategic markets: (a) coastal and inland shipping, (b) marine engineering (dredging), (c) offshore wind, and (d) maritime safety[101]. The programme aims to bridge the gap between R&D and large scale market deployment by testing a range of alternative fuels including hydrogen, methanol, and LNG with carbon capture. Government agencies will act as launching customers to reduce investment risk for industry, while the initiative is designed to boost Dutch maritime competitiveness and contribute to European maritime autonomy. Despite the funding approval a few years ago, progress on actual vessel construction is still in its early stages. This late start puts pressure on the original 2030 delivery target for all 40 ships, making delays likely unless development and build phases accelerate significantly[102]. However, the programme includes LNG combined with carbon capture and storage among its fuel pathways, fossil-based approach that increases rather than reduces climate harm.

Green Corridor Initiatives

A green corridor is a maritime route between two ports where zero- or near-zero-emission shipping solutions are deployed and supported by aligned infrastructure, regulations, and incentives at both ends. Rotterdam has launched the world's longest green corridor with Singapore, featuring pilot projects such as the first bunkering of mass-balanced liquefied bio-methane and planned trials for methanol and ammonia as marine fuels along the Rotterdam-Singapore corridor[103]. The Netherlands is also partnering with the UK on multiple initiatives, including the Tyne-IJmuiden, which aims to eliminate more than 850,000 tonnes of CO_2 emissions annually through the deployment of methanol-fuelled vessels[104]. Additional joint feasibility studies are underway to explore green corridor potential on several other UK–Netherlands routes[105, 106].

Direct Impact of Ports and Shipping: Drivers and Consequences

Shipping is responsible for roughly 3% of global human-caused (i.e., anthropogenic) GHG emissions, though estimates vary depending on the methodology used. Below is an overview of the latest available data from multiple sources, along with an explanation of the nuances between them.

Table 2.5 Comparison of global shipping emissions from IMO and ICCT using bottom-up voyage-based methods (2018–2023)

All Shipping (International + Domestic + Fishing) expressed in million tons (Mt)

Emissions Year	2018	2018	2023
Source	IMO 4th GHG Study	ICCT 2025	ICCT 2025
GWP 100-Year	CH_4 = 28 N_2O = 265	CH_4 = 29.8 N_2O = 273	CH_4 = 29.8 N_2O = 273
Total GHG (CO_2e)	1,076	886	911
Global anthropogenic GHG emissions	–	51,027*	52,963*
Shipping as % of global anthropogenic GHG emissions	2.89%	1.7%	1.7%
CO_2	1,056	869	900
Global anthropogenic CO_2 emissions	36,573	37,975*	39,024*
Shipping as % of global anthropogenic CO_2 emissions	2.89%	2.3%	2.3%
Black Carbon (BC)	–	0.088	0.088

International Shipping emissions in million tons (Mt) [Bottom-up, voyage-based]

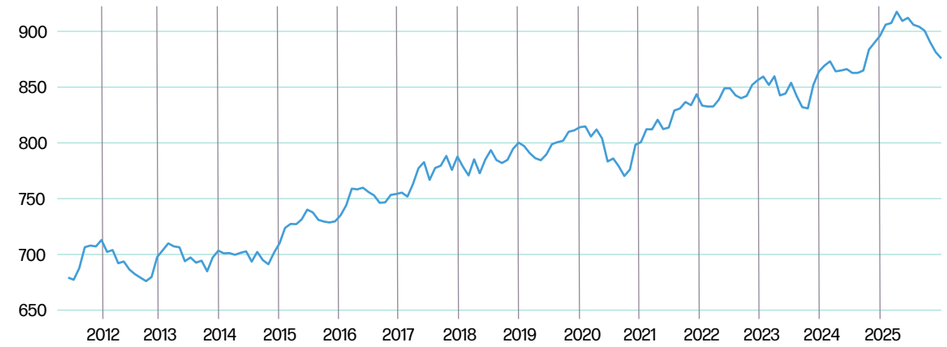
Emissions Year	2018	2018	2023
Source	IMO 4th GHG Study	ICCT 2025	ICCT 2025
GWP 100-Year	CH_4 = 28 N_2O = 265	CH_4 = 29.8 N_2O = 273	CH_4 = 29.8 N_2O = 273
Total GHG (CO_2e)	755	765	785
Global anthropogenic GHG emissions	–	51,027*	52,963*
CO_2	740	750	776
Global anthropogenic CO_2 emissions	36,573	37,975*	39,024*
Shipping as a share of global anthropogenic CO_2 emissions	2.02%	2.3%	2.3%
CH_4	0.140	–	–
N_2O	0.041	–	–
BC	0.062	–	–

Note. The ICCT study uses EDGAR's total anthropogenic emissions data, which includes CO_2, CH4, N2O and fluorinated gases but excludes large-scale biomass burning (savannah fires, forest fires) and land-use change emissions. This analysis compares IMO voyage-based, bottom up methodology with ICCT data as both approaches use AIS tracking to classify individual voyages as international or domestic shipping. Both methodologies align with IPCC guidelines for greenhouse gas inventory compilation, making this the most methodologically consistent comparison between the two sources.

Source. One Planet Port Foundation (2026), based on *IMO 4th GHG Study (2020)*; ICCT (2025), *Greenhouse gas emissions from global shipping*; and *EDGAR v7.0 anthropogenic emissions dataset*. Not covered by the OPP CC BY licence where third-party data apply.

According to the 2025 UNCTAD Review of Maritime Transport, shipping emissions have grown steadily over the last decade, with an estimated 5% increase from 2023 to 2024 due to continued ship rerouting and increased speeds. In the first half of 2025, a reduction in emissions was observed, probably reflecting slower sailing speeds, some operational improvements and the deployment of new ships[107].

Figure 2.7 Monthly annualized CO_2 emissions from global shipping (2012–2025)



Source. UNCTAD (2025), based on AIS data from Marine Benchmark. Not covered by the OPP CC BY licence.

Maritime emissions in the EU

Maritime transport accounts for 14.2% of EU transport-related CO_2 emissions, with annual emissions rising steadily since 2015. In 2022, monitored voyages emitted 137.5 million tonnes of CO_2, an 8.5% increase from 2021. Five vessel types (containerships, oil tankers, bulk carriers, chemical tankers, and general cargo) generated 80% of these emissions. EU fishing vessels emitted about 3.7 million tonnes of CO_2 in 2023, 2% of total transport emissions, down from 4.8 million tonnes in 2021, mainly as a result of fleet reduction[108].

Methane (CH_4) emissions from the sector are growing rapidly, driven by a 32.2% expansion of the LNG-powered fleet in 2022. Maritime methane emissions at least doubled between 2018 and 2023, reaching 14,000 tons in 2022 and representing 26% of the transport sector's total methane emissions. Methane has a warming effect of about 80 times stronger than CO_2 over a 20-year period, meaning even relatively small increases can significantly accelerate climate change.

Port Emissions in the EU

A study of European ports shows dramatic variations in reported carbon footprints, with direct port operations (Scope 1 and Scope 2) ranging from 0.017 to 1.27 kg CO_2e per tonne of cargo throughput[109]. Much of this disparity stems from different methodologies and operational boundaries, rather than actual performance differences. In particular, there is notable inconsistency in how ports calculate emissions, especially in the case of indirect emissions (Scope 3), making results difficult to compare. The lack of standardised accounting methods not only prevents reliable benchmarking but also undermines the sector's ability to set and track meaningful emission reduction targets across the sector[110].

International Climate Framework Agreements

The Paris Agreement[111], adopted by 195 countries in 2015, aims to limit global temperature rise to well below 2°C above pre-industrial levels, preferably to 1.5°C. It relies on voluntary nationally determined contributions (NDCs), in which each country sets its own emission reduction targets. According to the IPCC's 2022 assessment, limiting warming to 1.5°C requires emissions to peak before 2025 and fall by 43% by 2030. Despite strengthened commitments at annual COP meetings, current pledges remain insufficient. According to UNEP, continuation of current policies will lead to a catastrophic temperature rise of up to 3.1°C[112]. Even if current 2030 pledges are fully met, warming would still be limited only to 2.6–2.8°C[113]. UNEP highlights that meeting the 1.5°C goal is still technically possible, but would require a G20-led, massive global mobilisation to cut all GHG emissions across all sectors[114].

The Netherlands, both as an individual EU member state and part of the EU's collective commitment, is bound by the Paris Agreement.

The Montreal Protocol (1987), originally designed to protect the ozone layer, has also become an important climate instrument. Its 2016 **Kigali Amendment** mandates an over 80% phase-down of hydrofluorocarbons by the 2040s, a step projected to prevent up to 0.5°C of warming by 2100. HFCs are synthetic greenhouse gases used mainly as refrigerants in air conditioning, refrigeration, and heat pump systems, as well as in some aerosols and insulating foams.

Historically, it has been widely assumed that the Paris Agreement[115] does not cover emissions from international shipping, as the sector is an 'international' sector. However, NGOs Opportunity Green, Seas at Risk, and Transport & Environment (T&E) have called for the inclusion of shipping in national Paris climate targets[116]. Their joint statement cites several legal analyses arguing that shipping falls within the Paris Agreement's scope of *economy-wide emission* coverage, and that its exclusion is a *glaring gap* in most countries' climate plans.

IMO Regulations[117, 118, 119, 120]

The International Maritime Organization's (IMO) 2023 Revised Greenhouse Gas Strategy sets a target of achieving net-zero emissions from international shipping by around 2050, with indicative checkpoints of 20-30% reduction by 2030 and 70-80% by 2040. At Marine Environment Protection Committee (MEPC) 83 in April 2025, member states approved mid-term measures in the form of a Net Zero Framework (NZF) aimed at translating this strategy into binding regulation.

However, in October 2025, an extraordinary session of the MEPC voted 57-49 (with 21 abstentions) to postpone formal adoption for one year until October 2026, creating significant uncertainty about the framework's future and delaying its earliest possible entry into force to 2029.

The NZF adopts a dual-target approach to reduce greenhouse gas fuel intensity (GFI) of shipping. Under the NZF, each vessel must comply with both a Base Target and a Direct Compliance Target. The 2008 GFI reference value of 93.3 gCO_2e/MJ represents the average well-to-wake greenhouse gas intensity of ship fuels at that time and serves as the baseline for future reductions. Under the NZF, fuels and technologies qualify as Zero and Near-Zero (ZNZ) if their lifecycle GHG intensity is no higher than 19 gCO_2e/MJ until 31 December 2034, roughly an 80% reduction from the 2008 baseline. Achieving this threshold will require large-scale adoption of truly low-carbon fuels such as green hydrogen, green methanol, or advanced biofuels, going well beyond incremental efficiency improvements to conventional fossil fuels.

The expected emissions savings from the Net Zero Framework (NZF) are estimated at only a 10% ± 2% reduction in maritime emissions, falling well short of the ambition set by the IMO's Revised Greenhouse Gas Strategy. The mid-term measures are projected to raise $11-12 billion annually during their first three years, but the Greenhouse Gas Fuel Intensity (GFI) targets for the late 2030s cannot be met by incremental innovations alone. Liquefied natural gas (LNG), nearly all of which in global trade today is fossil-based, will face rapidly increasing penalties from 2033 onwards, while key implementation details, including the designation of responsible parties and enforcement mechanisms, remain undefined.

The Netherlands, both as an individual EU member state and part of the EU's collective commitment, is bound by the Paris Agreement to act on all emissions economy wide, which also includes shipping.

The IMO has established a two-phase review process for its short-term measures. The first review assessed the effectiveness of both the Energy Efficiency Existing Ship Index (EEXI) and Carbon Intensity Indicator (CII), including data collection systems, enforcement, and reduction factors. A subsequent review will examine how these measures can be integrated with mid-term policy instruments.

The Z factors (reduction factors) within the CII framework have been extended beyond 2026 (the required percentage improvements in carbon intensity that ships must achieve relative to a 2019 baseline). They are now set at 13.625% for 2027 and 21.5% for 2030, representing progressively more stringent improvements compared to the 2019 baseline. These targets will require significant efficiency gains and a shift towards low-emission fuels, meaning operators who delay upgrades risk falling out of compliance as requirements tighten.

EU Regulations

The EU Green Deal targets climate neutrality by 2050, with maritime transport covered under two main regulations: the EU Emissions Trading System (EU ETS) and FuelEU Maritime. Both apply to vessels above 5,000 gross tonnage (GT) and share a similar geographic scope, covering all intra-EU/EEA voyages, at-berth operations, and 50% of international voyages to or from EU/EEA ports (including designated transshipment ports).

From 1 January 2024, the EU ETS[121] includes tank-to-wake CO_2 emissions from ships engaged in commercial cargo or passenger transport. Methane (CH_4) and nitrous oxide (N_2O) will be included from 2026, and an expansion to smaller vessels (400-5,000 GT) is under consideration. Compliance obligations are being phased in, with 40% of covered emissions applied in 2024, increasing to 70% for 2025, and reaching full coverage at 100% from 2026.

The **FuelEU Maritime**[122] regulation entered into force on 1 January 2025. It requires a 2% reduction in greenhouse gas intensity of all energy consumed by the ship for its operation from 2025, measured against a baseline greenhouse gas (GHG) intensity of 91.16 gCO_2e/MJ. Over time, this target will become more stringent, requiring progressively cleaner fuels and technologies. The 2050 target is 80% reduction, which translates to a GHG intensity of 18.23 gCO_2e/MJ. Non-compliance results in financial penalties, while over-performance earns credits, creating a market-based incentive to adopt cleaner marine fuels.

Regional Emission Trading Schemes with maritime inclusions: The UK Emissions Trading Scheme (UK ETS)[123] will expand to cover domestic maritime emissions from 1 July 2026. It will apply to vessels of 5,000 gross tonnage and above, covering 100% of CO_2, methane, and nitrous oxide emissions from voyages between UK ports, including round trips that start and end at the same port. The scheme will also cover all in-port emissions within UK ports from both domestic and international vessels, representing around 46% of total UK domestic maritime emissions. A review is planned to assess extending coverage to smaller vessels (400–5,000 GT), and future expansion to include international voyage emissions is under consideration, particularly in the context of potential UK–EU carbon market linkage.

Turkey's Emissions Trading System (ETS) was initially expected to include maritime emissions following parliamentary approval in July 2024[124]. However, the Climate Law adopted in July 2025, along with its draft implementing regulation, focuses exclusively on stationary installations in power and industry sectors, with no provisions for shipping or maritime transport[125].

In Africa, maritime carbon pricing is emerging through the **Africa Sovereign Carbon Initiative**. Djibouti became the first country on the continent to implement a national carbon pricing mechanism for international shipping in March 2023, charging $17 per tonne of CO_2e based on 50% of voyage emissions[126], with a maximum charge of $7,500[127] per voyage. Gabon joined the initiative in early 2025. Both countries require monthly emissions reporting and payments within 45 days of invoicing. Carbon offsetting mechanisms were introduced in Djibouti in July 2025 and are scheduled to launch in Gabon in 2026[128] . Around 10 additional African countries are actively considering joining this initiative[129].

Financial Sector Climate Commitments

Financial sector climate frameworks can send market signals that influence capital allocation towards low-carbon investments and zero-emission technologies, though their effectiveness depends on voluntary adoption and enforcement.

The **Net-Zero Banking Alliance (NZBA)**, formerly a membership alliance of banks committed to achieving net-zero financed emissions by 2050, transitioned to a voluntary guidance framework in 2025 after numerous major institutions withdrew. At its peak, NZBA included over 140 banks from 44 countries controlling more than $40 trillion in assets[130]. Starting in mid-2024, several major institutions including JPMorgan, Citi, Morgan Stanley, Macquarie, Bank of Montreal, HSBC, Barclays, and UBS exited the alliance, ultimately leading to its transformation from a commitment-based membership organisation into non-binding guidance.

The **Poseidon Principles** now counts 35 signatories from 14 countries, representing nearly 80% of global ship finance (approximately $240 billion). This sector-specific framework established the first climate alignment methodology for shipping finance portfolios, using reported real-world emissions data[131]. Despite increasing transparency, portfolio climate alignment scores, which compare the carbon intensity of banks' shipping portfolios against the IMO's decarbonisation pathways, remain well off track. According to the 2024 Annual Disclosure Report, banks' portfolios were, on average, +19.4% more carbon-intensive than the IMO's minimum trajectory and +25% above the more ambitious "striving" trajectory[132], meaning financed fleets emitted far more than is consistent with either pathway. While these figures showed modest improvement from the previous year, they confirm that the ship finance industry remains misaligned with the IMO's 2050 net-zero target. Although results vary depending on portfolio composition and vessel types, the scores underscore the urgent need for technological innovation, fleet renewal, and targeted investment across maritime segments.

Green Finance Mechanisms and Taxonomies

The EU Taxonomy includes detailed criteria for maritime transport and energy infrastructure, but other jurisdictions are developing their own classification systems, leading to growing market fragmentation. Maritime sustainability-linked and green/blue/transition loans and bonds currently target different goals (such as reducing emissions intensity, financing green investments, or supporting nature restoration) and lack consistent methodologies. These taxonomic inconsistencies across regions create compliance burdens for shipping companies operating internationally, while the absence of standardised maritime green finance definitions hampers cross-border investment and raises transaction costs. At the same time, regulatory fragmentation opens the door to greenwashing, as companies may choose the most lenient framework available while still claiming adherence to environmental standards.

EU Sustainability Disclosure and Due Diligence Regulations are essential tools to drive change by requiring companies to actively prevent and address adverse impacts across their value chains.

Target Setting and Disclosure Frameworks

The **Science Based Targets initiative (SBTi)** provides maritime sector guidance[133] requiring absolute emission reductions aligned with 1.5°C pathways. At the global level, the **International Financial Reporting Standards (IFRS)** sustainability standards[134] (IFRS S1 and S2) aim to harmonise climate and sustainability reporting. The GHG Protocol[135] remains the most widely used guidance on Scope 1, 2 and 3 accounting across industries, while the **Partnership for Carbon Accounting Financials (PCAF)**[136] offers methodologies for measuring financed emissions, including those from maritime portfolios. Despite these advances, major methodological inconsistencies remain, particularly for Scope 3 emissions, while verification standards are still underdeveloped and reporting practices vary widely. This lack of comparability undermines the ability to evaluate progress or assess the real impact of interventions across the sector. In September 2025, the GHG Protocol and ISO announced a strategic partnership to develop unified global standards for GHG accounting and net zero, which may help address these fragmentation issues over time.

EU Sustainability Disclosure and Due Diligence Regulations

Corporate Sustainability Reporting Directive (CSRD): The CSRD aimed to enhance transparency and comparability of corporate sustainability information by requiring detailed, standardised reporting on environmental, social, and governance impacts using double materiality principles – assessing both how sustainability issues affect the company and how the company impacts society and the environment[137]. However, in a November 13, 2025 vote, the European Parliament agreed to dramatic cuts to the CSRD, raising reporting thresholds to 1,750 employees and €450 million in revenues and eliminating the obligation for companies to prepare climate transition plans, with 382 MEPs voting in favor and 249 opposed[138]. This position, resulting from an alliance between the center-right European People's Party and farther-right parties after a compromise deal was narrowly rejected in October, diverges significantly from the EU Council's more moderate June 2025 position, setting up contentious trilogue negotiations[139].

Corporate Sustainability Due Diligence Directive (CSDDD): The CSDDD was designed to establish mandatory human rights and environmental due diligence across corporate value chains, requiring companies to identify, prevent, mitigate, and remedy adverse impacts on people and planet – from child labour and pollution to deforestation – throughout their operations and business relationships[140]. However, the EU's Corporate Sustainability Due Diligence Directive, which entered into force in July 2024, has been significantly weakened through the European Parliament's November 2025 vote, which dramatically increased compliance thresholds to cover only companies with 5,000 employees and over €1.5 billion in revenues[141]. This represents a substantial narrowing from the original directive and leaves only the largest corporations within scope, with negotiations between Parliament and Council scheduled to begin in mid-November 2025 to finalise the legislation by year-end.

Together, these directives were designed as complementary accountability mechanisms: the CSRD creates transparency through mandatory disclosure of sustainability impacts and risks, while the CSDDD drives operational change by requiring companies to actively prevent and address adverse impacts across their value chains, with potential civil liability for failures. However, the dramatic scope reductions approved by Parliament in November 2025 significantly limit both directives' potential to drive corporate sustainability transformation across Europe.

Shore power, Ship and Port Electrification

Shore power (also known as cold ironing) supplies electricity from land-based grids to vessels while docked, eliminating the need to run their auxiliary engines. This significantly reduces local air pollution, greenhouse gas emissions, and noise in port areas. Shore power is also vital for charging batteries on hybrid and fully electric vessels, supporting the broader shift towards maritime electrification[142]. A key barrier to widespread adoption of shore power is the limited capacity of many port electricity grids[143].

Integrating batteries into ship design can improve efficiency by an estimated 2.5 - 25%[144] depending on the type of vessel, operation and system design. Batteries charged via shore power allows vessels to operate as plug-in hybrids or fully electric ships, cutting reliance on fossil fuels use especially during port stays, inland transport, and short-sea voyages. Globally, more than 900 battery-powered vessels are already in operation, with over 450 battery vessels on order[145].

Electrification of port equipment, such as ship-to-shore (STS) cranes, rubber-tired gantry (RTG) cranes, generators, and other cargo handling machinery, further reduces fuel consumption, delivering both financial savings and environmental benefits[146,147].

Energy Efficiency Measures[148]

Vessel energy efficiency measures can be operational or technological, and together they can deliver significant energy savings. Key categories include:

- **Operational practices:** vessel maintenance, operation and cargo handling practices
- **Propulsion and hull:** hydrodynamic performance improvements
- **Machinery:** main engines, auxiliary engines, and related systems
- **Energy consumers:** onboard equipment such as more efficient lighting and cargo handling systems
- **Wind-assisted propulsion:** rotor sails, wing sails, kites, and suction wings that harness wind power to reduce fuel consumption

Designing future port systems requires integrated, adaptive management practices.

Use of Alternative (low-carbon and carbon-neutral fuels, including advanced biofuels)

The transition to alternative fuels is critical to tackling the emissions reduction required after all savings are achieved from efficiency and optimisation measures, installing of energy saving devices and technologies such as wind. However, successful deployment requires comprehensive lifecycle assessment that accounts for production methods, supply chain emissions, land-use change impacts for biofuels, and operational issues including methane slip, nitrogen oxides (NO_x), nitrous oxide (N2O) and particulate emissions. Scaling these fuels also requires substantial infrastructure development at ports and along key shipping routes to ensure reliable availability. Long-term fuel off-take agreements between fuel producers and shipping companies are essential to provide market certainty and attract the investment needed to scale production. Finally, effective regulatory frameworks, backed by robust enforcement, are critical to create the stable policy environment required to accelerate the fuel transition at the required pace and scale.

Tenant Decarbonisation

Ports can accelerate tenant decarbonisation by combining supportive measures with clear accountability. Effective strategies that have been successful in other domains like commercial real estate include: providing technical guidance, providing financial incentives such as sustainability-linked lease terms, and infrastructure investment that enables tenants to adopt cleaner technologies. As collaborative initiatives and incentives mature, enforcement mechanisms will become increasingly important, both to ensure that commitments translate into measurable outcomes and to sustain momentum across the entire tenant community.

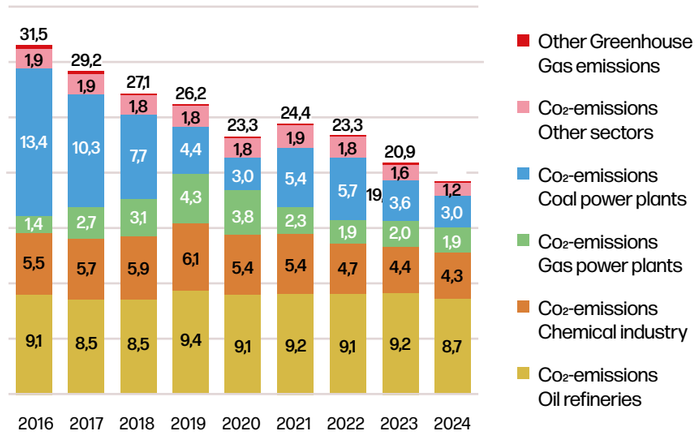
Systems Thinking for Modal Shift and Land Use Change

Designing future port systems requires integrated, adaptive management practices. This means creating feedback mechanisms and learning loops that enable port development to respond to changing trade patterns, technological advances, and environmental pressures. Modal shift and spatial planning must carefully balance the competing demands of maritime, industrial, and urban development while preserving flexibility to accommodate future energy transition needs. A systems approaches should incorporate emerging knowledge, for example, previously unquantified emissions sources, such as methane releases triggered by ship passages disturbing seabed sediments[149].

Current Contributions and Facts from the Port of Rotterdam

In line with international climate targets, the Port of Rotterdam Authority (PA) aims to achieve a climate-neutral port by 2050, with clear reduction targets for emissions under its direct operational control (Scope 1 and 2). Each year, the port reports on emissions from its own operations, shipping and the port industrial complex (PIC)[150]. PIC emissions constitute the largest share of the port's emissions.

Figure 2.8 Greenhouse gas emissions of land-lease companies in the Port of Rotterdam (2016–2024)



Note. Emissions represent Scope 1 and 2 emissions reported by land-lease companies. Categories include oil refineries, chemical industry, gas power plants, coal power plants, and other sectors.
Source. Port of Rotterdam Authority (2024), "*Greenhouse gas emissions of companies in the Port of Rotterdam down by 8%*," press release. Not covered by the OPP CC BY licence.

The Port Authority's (PA) emissions profile reflects its dual role as operator and facilitator. Emissions under the PA's direct operational control amounted to only 3.2 kton of emissions (Scope 1 and 2) in 2022, where ambitious targets aim for a 90% reduction by 2030. In contrast, around 20 Mton of emissions arise from the wider port ecosystem beyond direct control. Here, the Authority influences outcomes through infrastructure provision, policy frameworks, and industry collaboration, with a collective goal of achieving a 55% reduction by 2030.

The PA has developed targeted policies to embed CO_2 reduction goals directly into land-use agreements. New clients are required to operate carbon-neutrally from the outset, while existing tenants must enter sustainability agreements at contract review points. In addition, customised action plans have been developed for the port's 20 largest emitters. From 2024, companies receive land lease discounts of 2.5% (or 3.5% for net-zero operations) if they reinvest the same amount annually in sustainability measures, with large emitters required to submit verified reduction plans. From 2025, carbon reduction commitments become binding clauses in all new contracts and contract amendments. Progress will be monitored through mandatory reporting, and rebates may be reclaimed in cases of non-compliance[151].

Figure 2.9 Port of Rotterdam Authority greenhouse gas emissions and targets (Scopes 1–3)

Material topic	(Critical) Performance Indicators	Target 2030	Realisation 2024	Realisation 2023	Realisation 2022
PoR greenhouse	CO_2-emissions of PoR	Scope 1 & 2: -90% Scope 3: Contracter jobs 45%, Business travel and communiting -60% and shipping -20%	Scope 1 & 2: 853 ton Scope 3: contractor jobs 22.658 ton, business travel 390 ton, commuting 942 ton and shipping 2.157.000 ton		

Source. Port of Rotterdam Authority (2024), *Highlights Annual Report 2024*. Not covered by the OPP CC BY licence.
Note. In accordance with the Greenhouse Gas Protocol, a distinction is made between three types of emissions: scopes 1, 2 and 3. These three types of emissions and their translation into assessed emission sources at the Port of Rotterdam Authority are summarized in this diagram

Figure 2.10 Port of Rotterdam Authority emission categories, responsibilities, and Scope 1–3 definitions

Emission category	Scope 1	Scope 2	Scope 3
Emission sources Port of Rotterdam Authority	Own vessels and vehicles, and own real estate	Purchased electricity and districts heating	Contractor jobs (category 1), business travel (category 6), commuting (category 7) and shipping in the port area up to 60km offshore (category 11)
Responsibility	'Control' Results reporting requirement	'Influence' Effort obligation	'Influence' Effort obligation
Emissions target for 2030 (compared to 2019)	Scope 1) + Scope 2) -90%		Category 1: -45%, categories 6 and 7: -60% and category 11: -20%

Source. Port of Rotterdam Authority (2024), *Highlights Annual Report 2024*. Not covered by the OPP CC BY licence.

Table 2.6 Port of Rotterdam Authority CO_2 reduction targets by scope category (2019–2030)

Scope	Description	CO_2 reduction target 2019-2025	CO_2 reduction target 2019-2030	CO_2 neutral in year
1a	Vessels	75%	90%	present
1b	Vehicles	90%	100%	present
1c	Real estate (own use)	20%	90%	present
2	Purchased electricity and heat	40%	50%	present
3a	Business flights	70%	80%	present
3b	Employee commuting	40%	50%	present
3c	Contractor assignments (fuel)	–	45%	2040
	Contractor assignments (materials)	–	25%	2050
3d	Real estate commercial	–	45%	2040
3e	Shipping	–	20%	2050

Source. Port of Rotterdam Authority (2023), *Climate Targets 2030 – Port of Rotterdam Authority*. Not covered by the OPP CC BY licence.

Figure 2.11 Port of Rotterdam Authority Scope 1–3 greenhouse gas emissions (2019–2024)

In gross ton CO_2eq	2024	2023	2022	2021	2020	2019	Realisation Δ 2019 - 2023	Science based target Δ 2019 - 2030
Scope 1								
Own vessels and vehicles, and own real estate	692	1,582	2,600	2,645	2,992	3,242	-79%	-90%
Scope 2								
Purchased energy (Location-based)	1,878	2,100	3,400	2,270	1,838	2,950	-36%	–
Purchased energy (Market-based)	43	50	50	50	50	70	-39%	-90%
Scope 3								
Category 1: Jobs contractors	22,658	27,040	27,090	28,630	26,070	34,230	-34%	-45%
Category 6: Business travel	390	420	–	–	–	890	-56%	-60%
Category 7: Commuter traffic	942	1,010	1,390	900	1,380	2,230	-58%	-60%
Category 11: Shipping in the port area up to 60km offshore	2,157,000	2,162,000	2,428,000	2,564,000	2,494,000	2,277,000	-5%	-20%
Total								
Scope 1+2+3 (Location-based)	2,183,560	2,194,152	2,462,480	2,598,445	2,526,280	2,320,542	-6%	–
Scope 1+2+3 (Market-based)	2,181,725	2,192,102	2,459,130	2,596,225	2,524,492	2,317,662	-6%	–
Greenhouse gas intensity								
Emission intensity (Location-based)	2,476	2,607	2,982	3,363	3,354	3,284	-25%	–
Emission intensity (Market-based)	2,474	2,605	2,978	3,360	3,351	3,280	-25%	–

Source. Port of Rotterdam Authority (2024), *Highlights Annual Report 2024.* Not covered by the OPP CC BY licence.

For projects that reduce its own Scope 1 and 2 CO_2 emissions, the Port Authority applies an internal carbon price of €100 per tonne to guide investment decisions.

According to the 2024 Annual Report[152], research published at *portofrotterdam.com*[153] and an April 2025 update on PIC emissions[154], it appears that the PA's climate commitments operate on two distinct tracks with different scopes and accountability mechanisms. The first track covers the Authority's Science Based Targets initiative (SBTi) validated targets spanning direct operations and selected Scope 3 categories, e.g., contractor work, business travel, commuting, and shipping within the port area. The second track addresses the far larger emissions of the Port Industrial Complex (PIC), which totalled 19.2 Mton in 2024, but currently fall outside the SBTi framework and rely instead on separate policy, infrastructure, and industry collaboration measures.

These PIC emissions, the largest share of port-related greenhouse gases, would fall under GHG Protocol Scope 3, Category 13 (downstream leased assets), since they originate from industrial activities carried out by tenant companies on Port Authority-owned land. But the PA's pledge to cut PIC emissions by 55% by 2030 (a reduction of 9.3 Mton)[155] is a separate, non-SBTi-validated policy commitment, aligned with Dutch and EU climate targets rather than the 1.5°C science-based pathway that governs its other emission targets. This dual-track approach highlights the governance challenge facing port authorities: exercising direct control over their relatively small operational footprint, while relying on policy, infrastructure, and collaboration to influence the far larger industrial emissions that lie beyond their immediate operational boundaries.

The Port Authority, working with companies in the port and the Dutch government, is implementing a four-pillar energy transition strategy to create a future-proof port with net-zero CO_2 emissions. More than 80 projects are already underway to drive this transformation forward[156].

- **Pillar 1: Efficiency and Infrastructure**
  Increasing the efficiency of existing industry and building infrastructure for heat, CO_2, electricity and hydrogen. This includes carbon capture and storage facilities (such as Porthos), regional heat networks (WarmtelinQ), hydrogen pipeline networks, and electrical grid upgrades to support the transition to sustainable energy systems

- **Pillar 2: A New Energy System**
  Renewing the energy system by switching from fossil fuels to green electricity and hydrogen. This involves large-scale deployment of renewable energy sources (offshore wind farms, solar), establishing hydrogen production and import capabilities, and facilitating the transition from oil and gas-based energy to clean electricity and green hydrogen for industrial processes.

- **Pillar 3: A New Raw Material and Fuel System**
  Moving to a new raw materials and fuel system. This pillar focuses on developing and scaling sustainable alternatives to fossil-based raw materials and fuels, including biofuels, recycled materials, waste-to-chemical processes, and circular economy initiatives that transform the port's material flows from fossil-based to bio-based, recycled, and hydrogen-based feedstocks.

- **Pillar 4: Sustainable Transport**
  Making transport more sustainable. This addresses the decarbonisation of maritime shipping, inland navigation, and road transport through shore power installations, alternative fuel bunkering infrastructure, electric and hydrogen-powered inland vessels (RH_2INE, ZES battery containers), hydrogen truck corridors (HyTrucks), and charging infrastructure for electric trucks.

Together, these projects, and the production of hydrogen and biofuels, are expected to deliver a 23 million tonne CO_2 reduction. This is equal to 35% of the Netherlands' national reduction target for 2030 (65 million tonnes)[157].

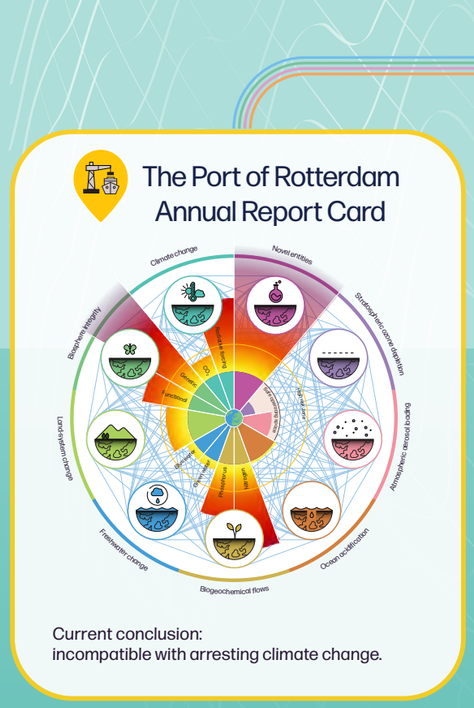
Recommendations for the Port of Rotterdam

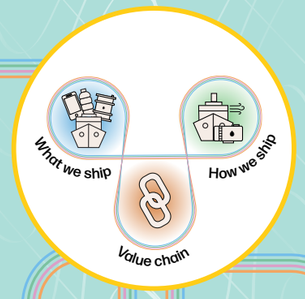
- **Establish a unified emissions reporting framework:**
  Integrate all emission categories (Scope 1, 2, and 3) into a single, science-based framework with mandatory third-party verification. Ensure that Port Industrial Complex (PIC) emissions are classified under GHG Protocol Scope 3 Category 13 (downstream leased assets), achieving consistency, and aligning with international standards while enabling robust benchmarking against other global ports. In September 2025, the GHG Protocol and the International Organization for Standardization (ISO) announced a partnership, aimed at reducing fragmentation in the GHG accounting landscape. An updated emissions standard from the partnership is expected; Rotterdam should monitor these developments to ensure alignment with emerging standards[158].

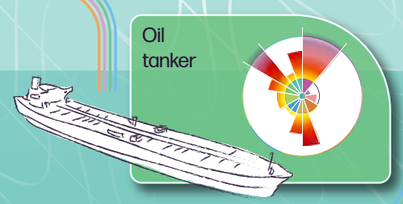
- **Implement consistent annual reporting cycles:**
  Align annual reporting across all emission scopes using standardized methodologies and reporting modalities. Publish both absolute values and percentage changes for each category to ensure year-over-year comparability. This will enable robust tracking of the 80+ ongoing transition projects, support evidence-based adjustments to the four-pillar strategy, and reinforce Rotterdam's leadership in international port networks such as the World Ports Climate Action Program (WPCAP) [159]. Consider leveraging EU CSRD timelines to reduce tenant compliance burden and accelerate implementation.

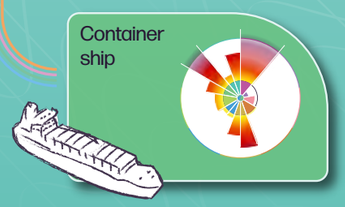
- **Implement comprehensive emissions monitoring:**
  Expand PoR's existing sensor network in phases, across the port area, to independently verify tenant-reported emissions data, monitor greenhouse gases not covered by EU ETS and track other pollutants affecting local air quality. Real-time monitoring capability would strengthen data integrity, provide early warning systems for environmental incidents (essential for local communities), and support the governance and impact evaluation of tenant incentive schemes such as land-lease discounts. It would also help the PA review tenants' transition action plans more effectively.

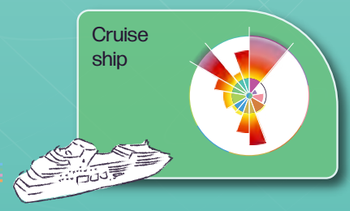
- **Expand reporting to include throughput emissions:**
  Develop throughput greenhouse gas and planetary boundary intensity metrics that account for both operational emissions and the embedded emissions, e.g., carbon, in cargo handled. Leverage Rotterdam's participation in the Carbon Measures[160] coalition to pilot product-level carbon tracking for goods moving through the port. Rotterdam's net positive[161] ambitions should expand beyond local environmental quality to encompass full climate responsibility for the industries the port chooses to serve. Such metrics would inform strategic decisions about which industries to prioritise in the 12,000-hectare port area, favouring low-GHG, circular economy businesses over high-GHG industrial activities. As carbon border adjustments and product carbon footprint regulations proliferate globally, tracking embedded emissions, i.e., throughput emissions impacts, in cargo will become essential for maintaining Rotterdam's leading position and aligning the port's strategy with its future earning potential in a decarbonising economy.











Global issue

As carbon border adjustments and product carbon footprint regulations proliferate globally, tracking embedded emissions, i.e., throughput emissions impacts, in cargo will become essential for maintaining Rotterdam's leading position and aligning the port's strategy with its future earning potential in a decarbonising economy.

Integrate planetary boundaries into climate decision-making:

Position Rotterdam as a pioneer in climate governance by recognising the interdependencies between climate change and the other eight planetary boundaries. There is growing interest in operationalising the planetary boundaries framework for decision-making at different levels[162]. While the World Economic Forum's Nature Positive report[163] demonstrates momentum in planetary boundaries thinking for ports, no port has yet operationalised this framework in climate strategy and investment decisions. Develop practical tools to assess how investments and tenant operations interact with biodiversity, freshwater systems, land use, and other boundaries that are inextricably linked to climate. Explore extending the current €100/ton carbon pricing methodology to develop comparable economic frameworks that account for co-benefits and trade-offs across multiple planetary boundaries. This integrated approach would strengthen Rotterdam's climate strategy by avoiding solutions that address greenhouse gas emissions while inadvertently transgressing other boundaries, positioning the port at the forefront of systems-based climate governance, and attracting forward-thinking companies, and workforce, aligned with sustainable transformation to the region.

Strengthen global coalition engagement:

Leverage Rotterdam's leadership positions in International Association of Ports and Harbours (IAPH)[164], WPCAP and Zero Emission Port Alliance (ZEPA)[165] to standardise emissions reporting methodologies across international port networks and terminal clients. Participate actively in Carbon Measures[166] to advance product-level carbon accounting standards that enable comprehensive tracking of embedded emissions in cargo throughput. Drive development of common metrics and best practice frameworks that can accelerate global port greenhouse gas reduction. WPCAP's integration with IAPH creates opportunities to influence global port standards, while ZEPA's Port Readiness Level methodology for alternative fuels supports standardised assessments at a more impactful level of granularity. Consistent reporting across these networks would create a critical mass of data to identify the most effective greenhouse gas reduction interventions and accelerate best practice sharing.

Accelerate shore power and alternative fuel infrastructure deployment:

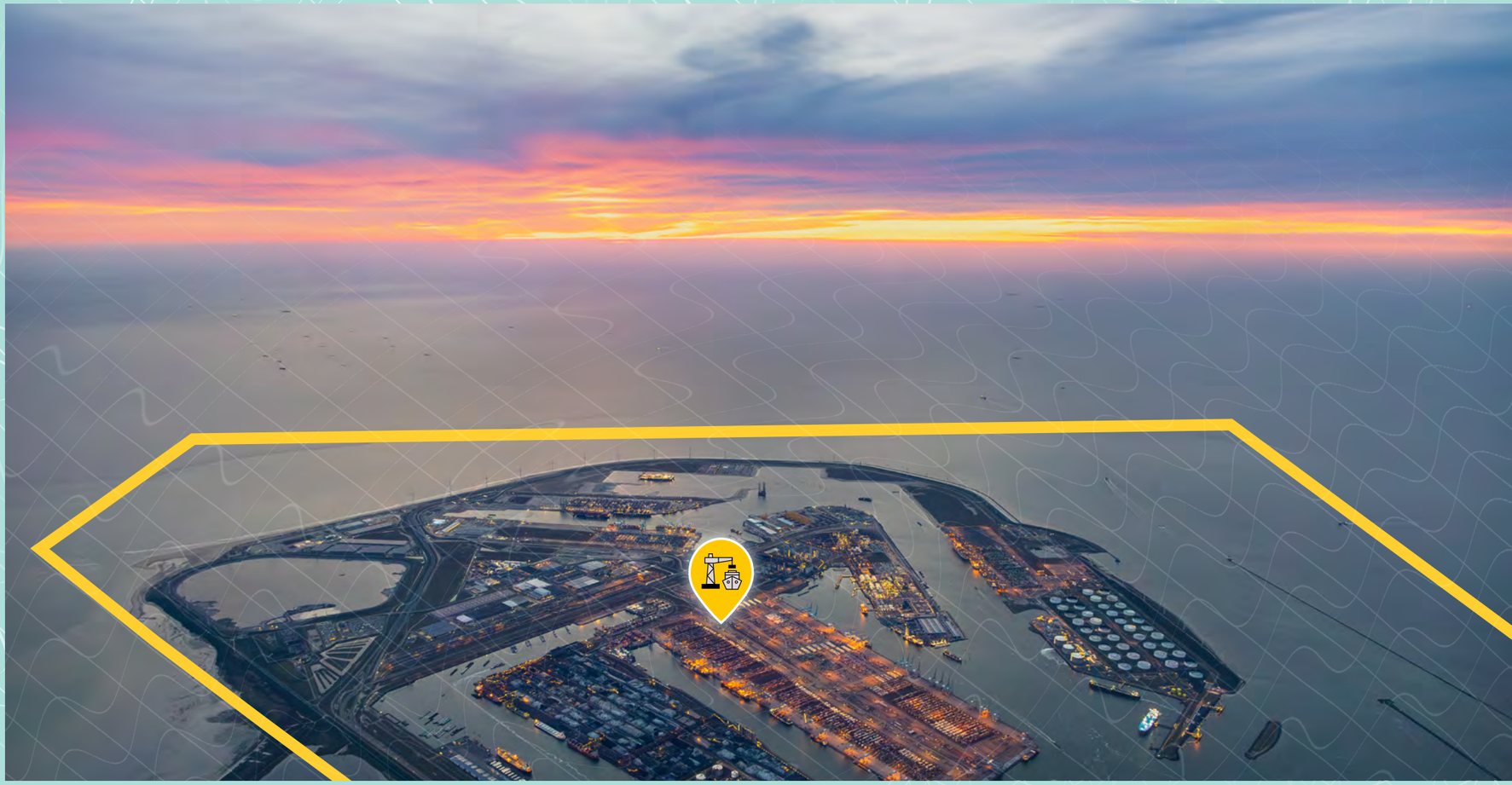
Fast-track development of shore power and alternative fuel bunkering facilities to capture first-mover advantage and support the IMO's 2030 zero-emission fuel uptake targets. Coordinate infrastructure investments with green shipping corridor partnerships.

Establish innovation bridge funding:

Create dedicated financing mechanisms to bridge the 'valley of death' between R&D and commercial scale technologies and projects. The funding opportunities should support the 80+ ongoing projects and emerging technologies through demonstration phases until they achieve bankability. Partner with development banks and green finance institutions to create blended finance mechanisms that reduce private sector risk while maintaining commercial incentives.

Develop comprehensive stakeholder engagement:

Develop a comprehensive stakeholder engagement program that includes local environmental groups, community organisations, and labour unions. Collaborate with NGOs to implement citizen science initiatives for air quality monitoring and bring local communities along in transition efforts. Create worker transition programs for alternative fuel handling and safety training. This approach would strengthen the port's social license to operate, and ensure that all relevant stakeholders become a part of and feel ownership for bringing about the required change(s).



A One Planet Port vision: Port of Rotterdam, thriving within the Planetary Boundaries.

Recommendations for Policymakers

- **Create an overarching Netherlands Maritime Greenhouse Gas Reduction Strategy:**
  The Netherlands currently implements maritime greenhouse gas reduction through a patchwork of initiatives, including the Maritime Master Plan, Green Deal commitments, IMO and EU regulatory compliance, various green corridor projects, and the Maritime Manufacturing Sector Agenda[167]. While valuable, these efforts operate in silos and lack a unified framework. There is no single strategy that maps international, national, and port-level initiatives against common timelines, assigns clear accountability, and closes policy gaps. An integrated strategy would enhance coordination between the responsible ministries, provincial authorities and municipal bodies, align diverse funding streams, and ensure the Netherlands maintains its leadership position while securing long-term sustainability and competitiveness of the Dutch maritime and ports ecosystem.

- **Increase Research and Development funding:**
  Substantially increase public funding for maritime greenhouse gas reduction research and demonstration projects at national level, and advocate for increased funding at EU level, focusing on nature-based solutions, propulsion technologies including modern wind propulsion, alternative fuels, systems integration and sustainable shipbuilding.

- **Implement Structured Capacity Building Mechanisms:**
  Develop workforce transition programmes to support maritime workers adapting to new technologies and alternative fuel systems required for greenhouse gas reduction, including safety training in handling alternative fuels, and upskilling for digital systems integration.

- **Scale safe piloting capability:**
  Establish regulatory frameworks and designated testing zones that allow controlled testing of innovative maritime greenhouse gas reduction technologies while maintaining safety standards (similar to EU AI Regulatory Sandboxes[168]). Build on existing facilities in Rotterdam such as DronePort Rotterdam (for testing autonomous and uncrewed systems) and the Fieldlab Industrial Electrification (FLIE) (for scaling electrification and hydrogen innovations)[169,170], while learning from successful international models. Enable rapid scaling of proven solutions through streamlined approval processes.

- **Mandatory climate risk assessments, monitoring and reporting:**
  Mandate comprehensive climate risk assessments for all major maritime infrastructure investments, considering direct and indirect emissions alongside the potential impact of sea level rise, extreme weather, and supply chain disruptions. Require periodic reassessments and incorporate lessons-learned into governance frameworks for future projects. This would ensure that funding is directed towards projects that are resilient and viable over the long-term.

Conclusion and Call to Action

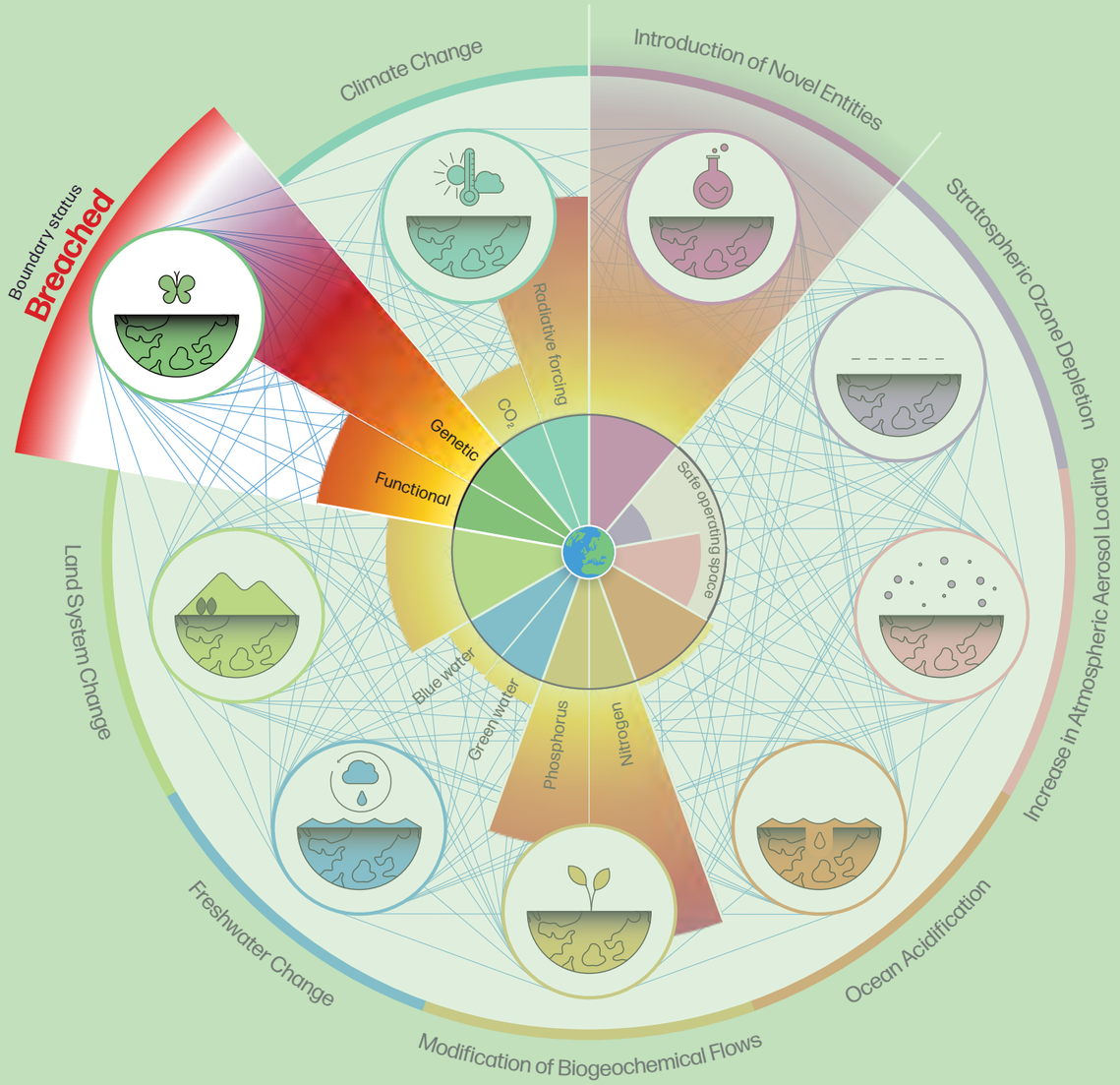
Climate change is the defining challenge of our time. With this planetary boundary severely transgressed, and multiple tipping points within the danger zone, urgent action is required to transform all aspects of how humanity interacts with the Earth system. Ports, as critical nodes of global trade and economy, are central to this transformation.

The Netherlands, and Rotterdam in particular, are well-positioned to lead this fundamental transformation of port ecosystems, drawing on world-class expertise, advanced infrastructure, and progressive policy frameworks to create a blueprint for the ports of the future. Yet the scale and pace of the transition demands unprecedented coordination, across government, industry, and civil society, at both national and international levels. The choices made today will determine whether we steer away from catastrophic climate futures while safeguarding the intergenerational prosperity and connectivity that modern civilisation relies upon. In the face of the climate emergency, incremental change is no longer an option.

As Elizabeth Kolbert observed in Under A White Sky:

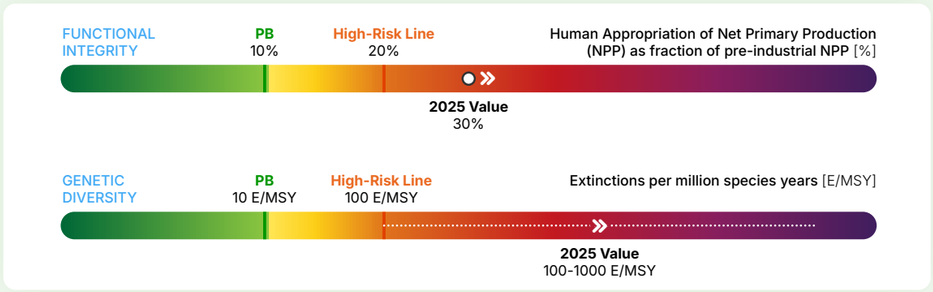
"If we want everything to remain as it is, everything must change."

CH3 Change in Biosphere Integrity



CH2 Climate Change
CH3 Change in Biosphere Integrity
CH4 Land System Change
CH5 Freshwater Change
CH6 Modification of Biogeochemical Flows
CH7 Ocean Acidification
CH8 Increase in Atmospheric Aerosol Loading
CH9 Stratospheric Ozone Depletion
CH10 Introduction of Novel Entities

Figure 3.1 Planetary Health Check 2025 status: Change in Biosphere Integrity

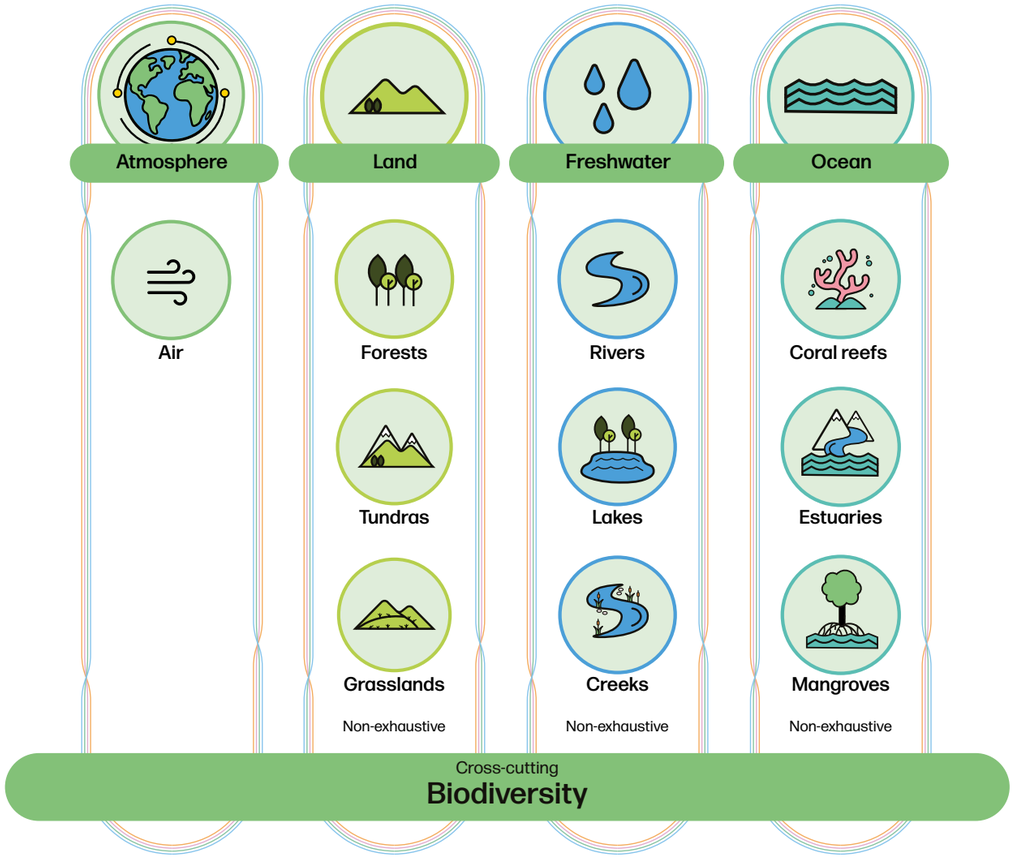


Source. *Planetary Healthcheck 2025*. CC BY 4.0.

Introduction to the Boundary (Global)

The biosphere is the Earth's ecological system that comprises all living organisms (biota) and the non-living factors, such as air, water, soil, and sunlight, from which biota get energy and nutrients. This is the Earth's entire zone of life, made of several ecosystems with their own distinct and uniquely adapted life forms. These can include forests, coral reefs, or desert ecosystems, featuring a diverse array of plants, animals, and even the smallest bacteria. A healthy biosphere is fundamental to a healthy planet as it enables key 'ecosystem services' like regulating air quality, moderating the effects of climate change, and supporting food chains.

Figure 3.2 Nature realms across atmosphere, land, freshwater, and ocean systems



Source. World Economic Forum (2024), *Nature Positive Guidelines for the Transition in Cities*.

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The Earth has faced five mass extinctions in the past. Now, human activities[171], including farmland expansion, overfishing, and logging, are driving a potential sixth extinction. Climate change, pollution, and the introduction of invasive species further intensify these pressures. About 2.17 million species have been formally identified[172]. However, estimates suggest that our planet may be home to anywhere between 3 and 100 million species[173]. Unidentified species are often found in inaccessible areas, such as the deep ocean or under the Antarctic ice, and may become extinct even before we learn of their existence.

Genetic diversity (measured in extinctions per million species-years, or E/MSY) and functional integrity (measured by the Human Appropriation of Net Primary Production or HANPP) are both critical indicators of the biosphere's health. The safe boundary for genetic diversity is set at less than 10 E/MSY, yet current extinction rates have skyrocketed to 100-1000 E/MSY[174], at least ten times higher than what is considered safe. This indicates a severe and accelerating loss of species.

Net primary production (NPP) is the rate at which plants and other photosynthetic organisms produce organic matter (biomass) in an ecosystem, after accounting for the organic matter they use for respiration. NPP serves as a proxy for the energy flow into the biosphere, which all life processes depend on. HANPP measures the extent to which human activities, such as agriculture, forestry, and urbanisation, 1) inhibit net primary production and 2) withdraw energy by harvesting products for human use and consumption[175].

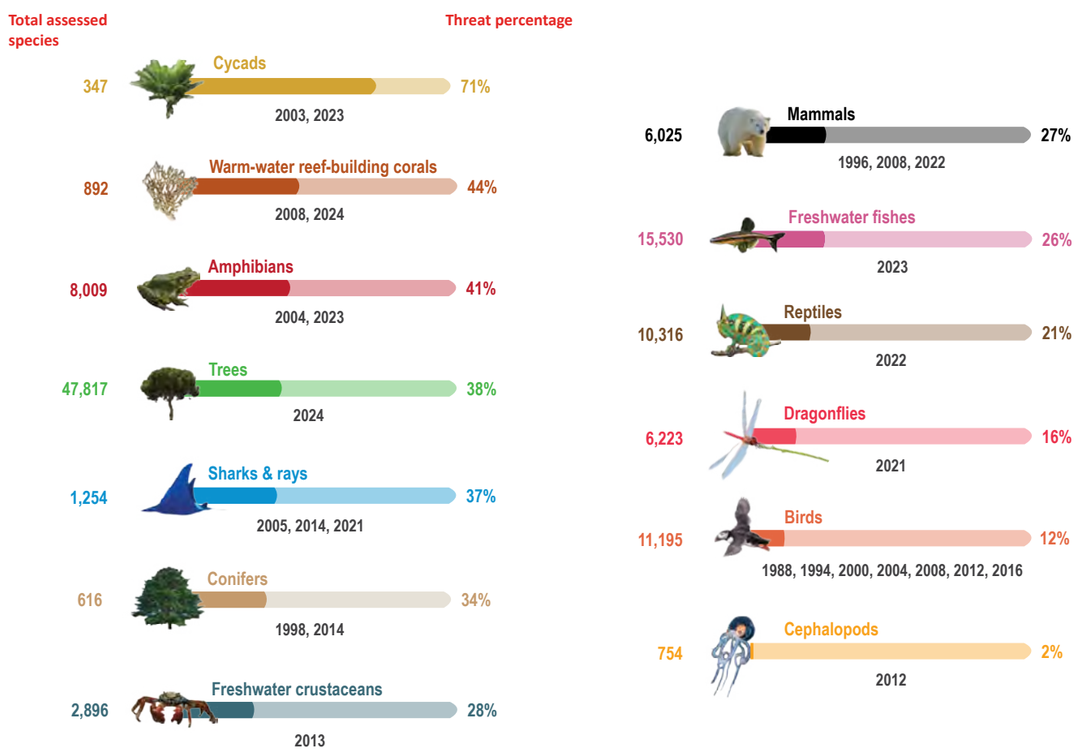
In the absence of human activity, HANPP would be zero; and for low-impact early human societies, it would be close to zero. The planetary boundary is set at less than 10% of the pre-industrial NPP and the current level is 30% – this means that humans are using 30% of the available energy from nature[176] – over 3 times the maximum amount that is sustainable, and putting us in the high risk zone.

The International Union for Conservation of Nature's (IUCN) Red List of Threatened Species has evolved to become the world's most comprehensive information source on the global conservation status of animal, fungi and plant species[177]. The IUCN Red List acts like an early warning system for biodiversity, showing which species are sliding towards extinction and where urgent action is needed. Based on the 2025 IUCN Red List data:

- To date, 172,600 species have been assessed for the Red List[178]
- 48,646 of assessed species are threatened with extinction[179]
- Amphibians, reef-building corals, cycad plants, sharks and rays, and trees have the highest proportions of threatened species, but all groups include species that are declining and close to extinction[180]

While improved monitoring partly explains rising numbers, the decline in biodiversity is real and accelerating. Firsthand experiences like catching fewer fish at long-time fishing spots[181], seeing fewer house sparrows on daily walks[182], or encountering far fewer insects on windshields[183] during countryside drives are not coincidences. These are now widespread, observable consequences of biodiversity collapse, aligning with what scientists are recording across ecosystems.

Figure 3.3 Threatened species among major taxonomic groups assessed in the IUCN Red List



Percentage of assessed species which are threatened with extinction, in groups of animals and plants that have > 80% of their known species assessed on the IUCN Red List, with dates underneath the bars showing the year of first and any subsequent reassessments
Source. International Union for Conservation of Nature (2025), *Red List: 60 Years of Success Report*. Not covered by the OPP CC BY licence.

If biodiversity decline is not addressed, the consequences will be severe, cascading across systems and largely irreversible within human lifetimes.

- **Disruption of ecosystem services:** Biodiversity underpins services like pollination, water purification, soil fertility (to grow food, stabilise the climate, and sustain ecosystems), and disease regulation (via regulation of hosts, e.g., rodents). As species disappear and ecosystems destabilise, these services start to break down. The loss of pollinators (such as bees, birds, bats) poses a serious threat to global food security by increasing the risk of crop failure, malnutrition and hunger. Animal pollinator collapse would take with it chocolate, coffee, and many fruits and vegetables[184]. Deforestation and wetland destruction disrupt water cycles, leading to droughts or floods, reduced CO_2 absorption, and ultimately greater climate instability and loss of agricultural and freshwater resilience. Marine biodiversity loss affects fish stocks, which more than 3 billion people rely on[185] for nourishment. Destruction of coastal ecosystems can increase susceptibility of coastlines to storms and sea level rise.

- **Destabilisation of earth systems**: The biosphere co-regulates planetary chemical cycles and energy balances. Its degradation can trigger feedback loops that worsen climate change and other planetary boundary overshoots, pushing the earth into a less stable and less habitable state. This means more frequent extreme weather, loss of freshwater supplies, food system collapse, spreading infectious diseases, rising sea levels, and large-scale displacement of people, especially in regions already facing social and economic vulnerability[186, 187].

- **Economic, social and human health implications**: It is estimated that 44% of the global GDP generated in cities, amounting to $31 Trillion, is vulnerable to disruption due to the loss of biodiversity[188]. The decline of industries like agriculture, forestry, fisheries, and tourism, which rely heavily on healthy ecosystems leads to job loss, economic instability, and increased poverty, especially in lower-income countries. Habitat destruction forces animals into closer contact with humans, increasing the chances of zoonotic* disease spillover. Risk of diseases like COVID-19, Ebola, and SARS grows with every acre of habitat destroyed. WHO advocates for strengthening health systems to be climate- and biodiversity-resilient by integrating biodiversity into public health policies through approaches like One Health, addressing infectious and noncommunicable diseases through whole-of-government, whole-of-society (everyone) approaches based on equity[189].

Loss in Biosphere Integrity is deeply linked to other planetary boundaries. Especially in the context of marine ecosystems:

Ocean Acidification impacts marine species and coral reefs

Climate Change alters marine ecosystems by changing their chemical and energy balance. Biodiversity conservation actions have mostly synergistic benefits and few trade-offs with climate change mitigation. For example, conserving coastal ecosystems like seagrass meadows and salt marshes protects biodiversity while acting as natural carbon sinks and strengthening climate resilience.

Introduction of Novel Entities, disruption of **Biogeochemical Cycles** and **Land-Use Change** affect both terrestrial and aquatic ecosystems, including benthic biodiversity.

* Infectious disease transmitted from animals to humans and vice versa.

National Context: Biodiversity in the Netherlands

Three main types of ecosystems predominantly characterise the Netherlands: Agroecosystems (used for food production) cover 63% of the country, followed by Urban areas occupying 16.8% of the land area, and Forest ecosystems accounting for 10%.

The Netherlands has relatively smaller proportions of rivers and lakes (8.3%), heathlands (1.3%), and wetland ecosystems (0.7%). Habitats protected in the Netherlands under EU law fall under the Habitats Directive. The Netherlands hosts 52 habitat types protected under the EU Habitats Directive, representing approximately 22.3% of the total 233 habitat types listed in the Directive. Among these Dutch habitat types, coastal and inland dune habitats form the largest group, accounting for 23%. Grasslands and coastal salt-tolerant habitats follow, each making up about 15.3% of the protected habitats in the country[190].

34.6% of habitat assessments indicate a poor conservation status, and 53.8% report bad conservation status, far surpassing the EU average of 35.8%. This underscores a serious failure to protect and restore these vital ecosystems, highlighting an urgent need for decisive action.

Given the extent of agroecosystems and urban areas[191], there is significant potential for nature-inclusive urban development (an approach that integrates natural elements and habitats into city planning to support biodiversity and improve quality of life) and green infrastructure in cities.

The Dutch government has established comprehensive policy frameworks to address biodiversity decline, including the National Nature Vision and the Nature Network Netherlands (Natuurnetwerk Nederland). The latter serves as the spatial backbone for biodiversity conservation by connecting existing protected areas through ecological corridors. The Netherlands is also bound by EU-level commitments under the Habitats Directive and Birds Directive, which establish the legal framework for the country's 162 Natura 2000 protected areas[192]. However, major implementation challenges remain, as evidenced by the concerning fact that only 11.5% of protected habitats assessments indicate a good conservation status, which is well below the EU average of 14.7%. This means that nearly 9 out of 10 protected habitat types are not thriving, even under supposed legal protection, which implies issues with either the design of protections or their enforcement.

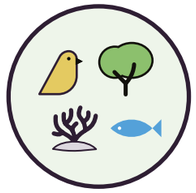


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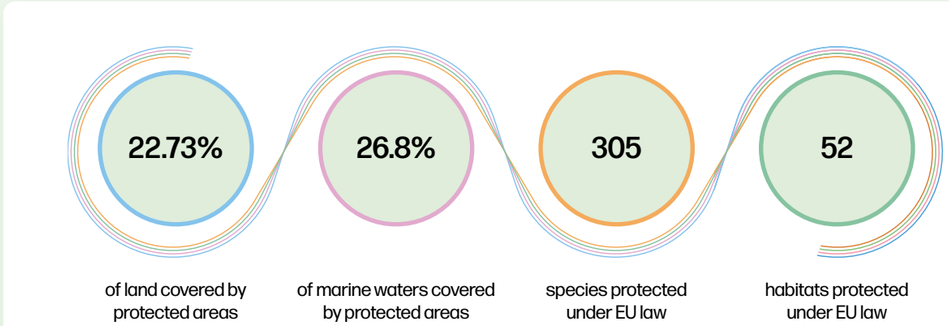
Figure 3.4 Key biodiversity protection indicators for the Netherlands under EU law



Source. European Environment Agency (2024), *EU Biodiversity Data – Netherlands Country Profile*. Not covered by the OPP CC BY licence.

Direct Impacts of Shipping and Ports: Drivers and Consequences

Water discharges: Discharges from open-loop exhaust gas 'cleaning' systems (EGCS) harm the marine environment as contaminants contribute to bioaccumulation (buildup of toxic substances in an organism over time), acidification (lowering of pH in water, making it more acidic), and eutrophication (excess nutrient enrichment which triggers algal blooms that lead to oxygen depletion, causing mass die-offs and suffocation of marine life). This underlines the need for further risk assessment and regulatory measures.

EGCS discharges account for 98% of permitted water discharges annually, as open-loop scrubbers allow ships to continue burning cheaper, high-sulfur, low-grade fuel instead of switching to more expensive low-sulfur fuel oils under EU and IMO sulfur emission regulations[193]. The remaining 2% of water discharges include grey water (wastewater from sinks, showers, laundries), sewage, bilge water (oily water that collects in the bottom of a ship from leaks, spills, and machinery), and discharges from closed loop scrubbers (which typically use seawater to extract sulfur from exhaust gases before discharging the waste along with contaminants including polycyclic aromatic hydrocarbons (PAHs) and heavy metals back into the sea). The volume of grey water discharged has increased by about 40% between 2014 and 2023, primarily due to the growing number of cruise ships in operation[194].

From the start of 2025, the use of open-loop scrubbers for berthed seagoing vessels has been restricted in the port of Amsterdam[195]. Seagoing vessels with a hybrid scrubber system must switch to closed-loop mode (with waste either collected for processing at port facilities or dumped in permitted offshore waters), or switch to a cleaner fuel that meets the sulfur environmental standards, such as Marine Gas Oil (MGO). A similar open-loop ban is already in place in the ports of Antwerp, Hamburg, and several French and Scandinavian ports[196].

In March 2025, the Dutch government announced that seagoing vessels will soon be prohibited from discharging scrubber wastewater into all Dutch ports and inland waters. Additionally, in June 2025, the OSPAR Ministerial meeting decided to ban open-loop scrubber discharges in internal waters and port areas throughout the North-East Atlantic (OSPAR Maritime Area) by July 2027[197]. Discharges from closed-loop scrubbers, which produce lower volumes but more concentrated waste, will be banned by January 2029[198].

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Marine debris: While shipping contributes a relatively small portion (1.8%) of regional European marine litter compared to fisheries, the sector generates 141-279 tonnes of plastic pellet pollution annually from European industries alone[199], equivalent to about 1 million lentil-sized (20 – 25 mg) pellets entering the ocean per hour, creating immediate and long-term environmental and health impacts that persist in marine ecosystems.

Physical impacts: Ship strikes pose increasing collision risks to whales and turtles, particularly in high-traffic areas like the Greater North Sea and Bay of Biscay, with notable increases in collision risks within Natura 2000 protected areas from 2017-2022. Additionally, approximately 27% of Europe's near-shore seabed suffers physical disturbance from maritime transport activities, including anchoring, dredging, and port operations, with 4.2% of broad benthic (seabed) habitats directly disturbed by these activities[200].

Habitat loss from port expansion: European port areas expanded by 12.5% between 2000-2018, destroying critical shallow-water sandy and muddy habitats that support diverse species, including seagrass beds, mangroves, saltmarsh ecosystems, and essential nursery areas for fish, bivalves, and crustaceans through land reclamation and dredging activities[201].

Deep-sea mining: While commercial deep-sea mining has not yet begun, the European Union has adopted a precautionary approach, advocating that marine minerals cannot be exploited before the effects of deep-sea mining on the marine environment, biodiversity and human activities have been sufficiently researched[202]. Scientists warn that biodiversity loss could be inevitable and irreversible, with mining operations potentially disturbing 8,000-9,000 square kilometres of seabed, an area the size of Cyprus, over a 30-year license period[203]. Deep-sea mining could exacerbate existing ocean pressures, causing irreversible biodiversity loss, habitat destruction, sediment plumes that spread 10-100 kilometres beyond mining sites, and the release of toxics and stored carbon, threatening Europe's deep-sea ecosystems[204] that not only serve as critical carbon sinks, but also support undiscovered species essential for ecosystem functions. Ports would serve as critical nodes in the deep-sea mining supply chain, linking ocean-floor extraction to land-based processing and distribution. Allseas – one of the foremost companies advancing deep-sea mining – is headquartered in Switzerland, operates from Delft, and services its vessels through the Port of Rotterdam.

Underwater radiated noise (URN): Underwater noise from human activities can impact marine organisms from invertebrates to fish, marine mammals, and diving seabirds in complex ways[205]. URN can reduce communication ranges and mask important signals, disrupt reproductive and resting behaviours, interfere with foraging, and exclude animals from important habitats, which in some cases may increase their exposure to other human impacts. In addition, stress responses, which weaken overall health and fitness, have been observed in several species. Noise can also cause temporary loss of hearing sensitivity and permanent loss of hearing ability, induce physical injury, and, in extreme cases, cause behavioural or physiological responses that may lead to death[206].

While URN has received comparatively less attention than other pollutants, it is now gaining important focus at both the international and European level, as reflected in the IMO's recent Revised Guidelines for the Reduction of URN from Shipping to Address Adverse Impacts on Marine Life[207] and is addressed by the EU Marine Strategy Framework Directive (MSFD). Under the MSFD, it was agreed that no more than 20% of a given marine habitat area should be exposed to high levels of continuous underwater noise over a year. The EU Zero Pollution Action Plan also requires the monitoring of underwater noise levels and its adverse effects in EU marine waters[208].

Tankers and cargo ships emerge as primary contributors to URN, particularly at lower frequencies. However, the contribution of specific ship types varies across regions and frequency bands, highlighting the complex interplay of factors influencing URN distribution. Foresight analysis indicates that the implementation of technical and operational URN and GHG mitigation measures may lead to a substantial reduction in URN for all ship types and in all regions by 2050. In specific cases, this reduction could be as much as 70% compared to the business-as-usual scenario[209].

Introduction of invasive and non-invasive species: Invasive alien species are animals, plants or other organisms that are introduced by humans, either intentionally or accidentally, into places outside of their natural range, negatively impacting native biodiversity, ecosystem services or human economy and well-being[210]. Non-indigenous (also non-native or non-invasive) species (NIS) are those species introduced outside their natural past or present range which might survive and reproduce. Some of the NIS can be harmless, with negligible impacts on native species. Other NIS can be invasive with potential to change native community composition and cause local population extinction with long lasting impacts which threaten biodiversity and ecosystem services. Those are addressed by the EU Regulation 1143/2014 on Invasive Alien Species which includes some marine species[211].

Shipping introduced 60% of the non-invasive species (NIS) and 56% of invasive alien species (IAS) into European waters in 2017. The International Ballast Water Management Convention entered into force in 2017, and by 2023, 31% of the ships held International Ballast Water Management Certificates, while 23% had compliant ballast water management systems[212]. While the number of NIS keeps increasing, the introductions of IAS peaked in 2000-2005 and has since decreased. Only 18-21% of the MSFD assessed marine areas are in a good state regarding NIS[213].

Zebra mussels have caused significant ecological damage to the Great Lakes since their introduction in the 1980s through ship ballast water[214]. They have been identified as the invasive species with the greatest negative impact on local aquatic life in the Great Lakes[215]. The elimination of native clams from heavily infested areas is the most clear and dramatic impact. Zebra mussels promote harmful algal blooms[216] and are linked to a decadal decline in Lake Whitefish production due to clogged spawning reefs[217].

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56% of invasive alien species (IAS) into European waters in 2017.

Solutions and Maritime Interventions

Addressing the decline in biosphere integrity requires a comprehensive approach that not only spans policy frameworks, technological innovation, and financial mechanisms across local and global scales but also prioritises reducing material and energy flows and phasing out the most harmful activities driving biodiversity loss.

Kunming-Montreal Global Biodiversity Framework (GBF)[218]: The framework sets global targets to be achieved by 2030 and beyond, aimed at safeguarding biodiversity and ensuring its sustainable use[219]. The GBF aims to halt and reverse nature loss amid a dangerous decline threatening the survival of one million species. Key targets include protecting at least 30% of terrestrial and marine areas by 2030, recognising indigenous and traditional territories, and closing the $700 billion biodiversity finance gap (the difference between the amount of funding currently available for biodiversity conservation and sustainable use, and the amount actually needed to halt and reverse biodiversity loss)[220].

Agreement on the Conservation and Sustainable Use of Marine Biological Diversity of Areas Beyond National Jurisdiction: Also commonly referred to as the BBNJ Treaty or High Seas Treaty[221], is a landmark international agreement adopted on June 19, 2023 under the United Nations Convention on the Law of the Sea (UNCLOS). It aims to protect marine life in areas beyond national jurisdiction – the high seas and the deep seabed. The treaty focuses on the conservation and sustainable use of biodiversity, addressing issues like marine genetic resources, area-based management tools (including marine protected areas), environmental impact assessments, and capacity building. 84 countries have ratified the BBNJ as of January 2026. The treaty reached the required threshold of 60 ratifications on 19 September 2025. The Netherlands has signed the treaty but is yet to ratify it[222].

Habitat protection and supporting nature-based solutions: Globally, at least 20-25% of relatively diverse semi-natural habitat in each km² of land area is needed to maintain a minimum level of multiple ecosystem services, including pollination, pest and disease control, water quality regulation, soil protection and recreation[223]. Today, more than 60% of human-modified lands have less than 20% semi-natural habitat per km² and require immediate attention[224].

Nature-based solutions to climate change include protecting, managing, and restoring forests. Ocean habitats such as seagrasses and mangroves can sequester carbon dioxide at rates significantly higher than terrestrial forests – with some studies showing rates of ten[225] to thirty five[226] times faster.

Regulations need to promote and incentivise habitat preservation and serve as the cornerstone for tackling biosphere integrity. At the recent United Nations Ocean Conference, marine protected areas were extended – the world's largest MPA, led by French Polynesia will cover 5 million sq km, with 1.1 million sq km fully protected[227]. With more than 48,600 species documented as being at risk of extinction, preventing current extinctions is more urgent than attempting to reverse past extinctions[228].

Technological solutions: AI-powered monitoring solutions and predictive models[229], remote sensing, environmental DNA (e-DNA) developments (e.g., monitoring entire fish communities simply by analysing water samples for eDNA[230]), and drone technology can make conservation efforts more efficient and effective while potentially facilitating new ways of engaging the public on conservation issues[231]. AI and drone technology can help make the most of limited conservation budgets as more can be achieved with fewer resources and manpower.

Business and finance solutions: Corporate integration of biodiversity considerations is expanding as companies recognise both the risks and opportunities associated with nature dependence[232]. In some jurisdictions like the EU, businesses may be required to measure, disclose, and reduce their biodiversity impacts through emerging regulatory frameworks and standardised reporting systems[233]. Biodiversity accounting faces far greater complexity than carbon accounting, as biodiversity involves multiple dimensions that cannot be reduced to a single metric[234]. While biodiversity credit markets are emerging, they remain highly immature and face deep uncertainties about measurement standards and effectiveness[235]. Using biodiversity credits for offsetting has also been criticised as conceptually flawed because biodiversity is non-fungible. No two ecosystems or species are identical; therefore, genuine offsetting is impossible[236].

Individual and collective action: Building public awareness about consumption choices and their connection to biodiversity loss can contribute to change. Conservation approaches[237] and national biodiversity strategies significantly underutilise individual behaviour change with only 11% of policy actions specifying individual behaviours[238]. Beyond personal consumption, people can advocate for corporate accountability and stronger regulations. Most behavioural science interventions lack robust impact evaluation at scale[239]. Individual actions are necessary but insufficient without systemic policy changes and enforcement.

The most effective approaches to addressing biodiversity loss combine systemic changes, global policy frameworks, technological innovation, business transformation, and community engagement. Success depends on both accountability mechanisms and genuine reduction of harmful activities, not just disclosure or offsetting.

Current Contributions and Facts from the Port of Rotterdam

Port and shipping activities significantly contribute to indirect biodiversity loss by facilitating global trade in products whose production harms ecosystems. A study by Leiden University[240] highlights how European consumption of imported goods, such as fish (for use as animal feed) from Peru and cotton from Tanzania, drives environmental degradation abroad. These impacts include overfishing, habitat destruction, and pollution from agricultural practices. Ports and shipping not only enable the movement of these goods but also introduce additional ecological pressures, such as the spread of invasive species through ballast water and physical disturbances to marine habitats. Consequently, consumers in importing countries share responsibility for biodiversity declines in exporting regions. Addressing this issue requires increased awareness among stakeholders and the development of sustainable trade practices that consider the environmental costs embedded in global supply chains.

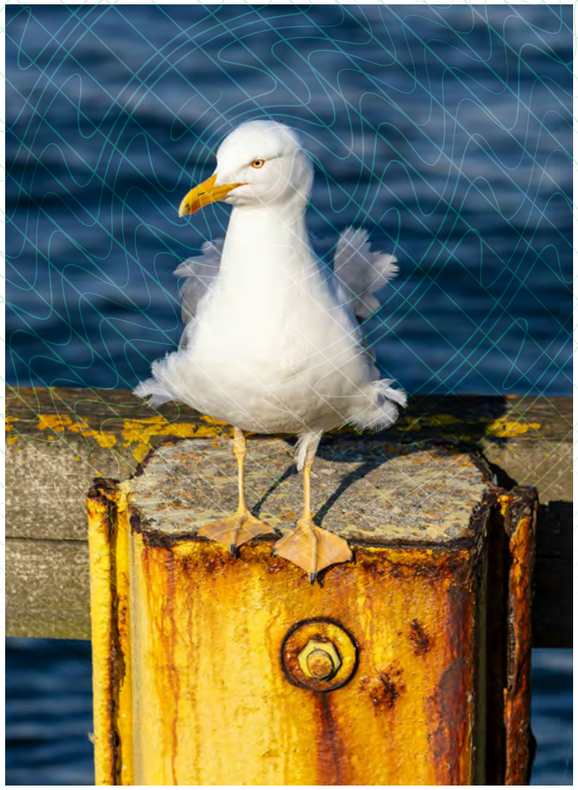
The Port of Rotterdam has developed a comprehensive Nature Vision[241] that integrates biodiversity conservation into its operations and expansion plans, recognising that economic progress should not come at the expense of local environmental health. The updated vision document (published in 2025) aims to integrate nature and biodiversity into the culture of the Port Authority, suppliers, and customers. It also references the European CSRD (Corporate Sustainability Reporting Directive) as part of its external reporting, which requires companies to report on their direct and indirect impact. The Port Authority's long-term goal is for all its activities to make a net positive contribution to society.

The Port Authority has several ongoing nature and biodiversity-related initiatives and actively devotes itself to conserving local nature and helping it develop. While operating adjacent to the Natura 2000-protected Voordelta marine area, the port has successfully created diverse habitats that support over 200 unique plant and animal species, including protected species like the natterjack toad and the fen orchid. 'Ecological stepping-stones' have been constructed at strategic locations in the port. Via these locations like verges, pipelines and corridors, plants and animals can migrate without interaction with humans[242].

- The first goal for an increase in biodiversity was set in May 2022: +5% increase in habitat surface area or ecological quality (biodiversity value) within the port area in 5 years (2022 – 2027)[243]
- A port survey of IUCN Red List species was conducted, and a map of biodiversity hotspots in the port was created[244]
- To track progress, the long-term monitoring network for grasslands was expanded by 67% in May 2022, with 10 additional plots established along forest edges and 10 along waterways, bringing the total to 50 plots. These sites are surveyed every three years for plants, butterflies, grasshoppers, and bees[245].
- Gulls, other coastal birds, fish and seals in the harbour are also monitored[246].
- Between 2022 and 2024, nine measures aimed at promoting biodiversity in site maintenance were implemented, including preserving tree canopies, using natural fertilisers, and transforming canalised waterways with revetments into nature-friendly banks[247].
- A digital toolkit with 21 nature-inclusive measures (like introducing green facades, creating nature-friendly banks, providing nesting opportunities for birds, creating ecomodules and reef structures, etc.) for development projects was launched in 2024[248]. This toolkit also links the specific measures to the locations where they are applicable, to enable tenants to choose the right measures to create an impact.

Approximately 2,455 hectares (equivalent to 3 Rotterdam city centres) of the Voordelta Natura 2000 area were utilised for the construction of the Maasvlakte 2[249]. To compensate for this loss, the Dutch Ministry of Agriculture promised that the natural values (biological richness, habitat integrity, and ecosystem health) in 25,000 hectares of the Voordelta would be improved by 10% by banning heavy beam trawling industrial fishing from the area. But the promised measures to make up for the environmental damage weren't properly implemented. Seven nature organizations, led by Natuurmonumenten, successfully sued the Dutch government in 2022 for failing to implement biodiversity compensation measures required for the construction of the Maasvlakte 2[250]. The court ruled that the government must enforce the original 2008 agreements, which had been ignored for 14 years. Despite political resistance and delays, fishing restrictions were implemented in approximately 27,900 hectares of the Voordelta marine area in 2024. While the final measures were less comprehensive than the original 2001 plan, the case represents a significant legal victory forcing the government to honour its environmental commitments. However, past failures raise serious doubts about the credibility of future compensation promises, especially in the context of a possible Maasvlakte 3.

Any potential expansion of the Port of Rotterdam, like the Maasvlakte 3, would likely require even more robust compensation measures than Maasvlakte 2, including upfront guarantees and binding timelines for compensation. To proceed with such plans, the Port Authority must demonstrate not only that current compensation is working effectively, but also that the Port Authority can deliver on new, even larger and more ambitious environmental commitments.



Recommendations for the Port of Rotterdam

- **Implement Transparent Third-Party Environmental Monitoring:**
  Establish comprehensive third-party environmental monitoring systems with transparent public reporting to build credibility and public trust in environmental performance across all domains, including emissions, water quality, and biodiversity.

- **Establish Biodiversity Footprint Accounting and Monitoring Across the Value Chain:**
  A robust approach to biodiversity management requires a footprint accounting and monitoring system for throughput-impacts throughout the port's value chain, including those of the tenants. This may include requiring biodiversity impact disclosures from tenants, assessing the biodiversity implications of traded goods passing through the port, and integrating these insights into port-wide targets and strategies. Such monitoring could be supported by collaborations with NGOs, academia, and data providers leveraging biodiversity footprinting, eDNA analyses in supply chains, and advanced satellite tracking of commodity origins.

- **Mandate Biodiversity Action Plans for All Tenants:**
  Require biodiversity action plans from all tenants and leaseholders. In addition to internal port operations, push tenants to adopt science-based biodiversity targets (analogous to emissions targets).

- **Incentivise Biodiversity-Friendly Shipping Practices:**
  Use port fees or discounts to reward ships using more biodiversity-friendly fuels, deploying wind propulsion or practicising slow steaming which reduces whale strikes and underwater noise.

- **Prioritise in-port optimisation over new expansion:**
  Rather than expanding into new marine areas (like the potential plans for Maasvlakte 3), the Port of Rotterdam should adopt a strict "no new virgin capacity" approach. This involves phasing out or scaling down the most environmentally harmful activities within the existing port area to free up physical and environmental capacity for strategic new uses. Through targeted phase-out plans, redevelopment corridors, and conditional leasing, the port can accommodate future economic activities without claiming additional natural space, thus aligning with planetary boundaries and demonstrating true environmental leadership.

- **Increase awareness of biodiversity initiatives:**
  Highlight ongoing projects in the Port of Rotterdam to build support and inspire further action among the port community and the public.

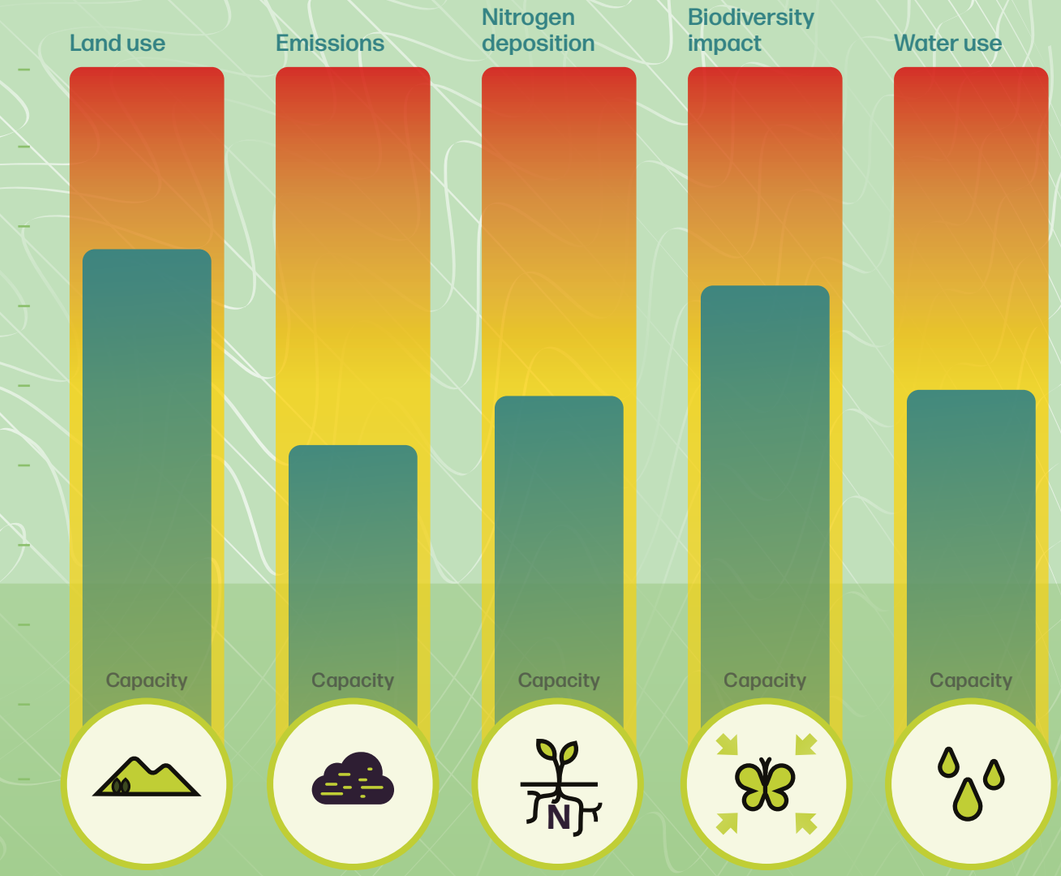
- **Strengthen Sediment and Benthic Biodiversity Monitoring and Restoration:**
  Support sediment quality monitoring, and benthic biodiversity monitoring, preservation and restoration efforts, recognising these as key building blocks for the restoration of larger aquatic life.

- **Continue marine ecosystem restoration efforts:**
  Expand the network of artificial reefs and habitat corridors.

- **Penalise discharges from vessels using scrubbers:**
  Scrubbers are used in combination with heavy fuel oil and scrubber discharges harm marine water quality, damage coastal ecosystems and nursery grounds, and increase cumulative environmental stress.

Recommendations for Policymakers

- **Set and Enforce a Fixed Environmental Capacity Budget:**
  Set and enforce a fixed environmental capacity budget for port areas with integrated limits on land use, emissions, nitrogen deposition, biodiversity impact and water use, ensuring operations and expansions stay within scientifically defined safe operating spaces.



The Port of Rotterdam

Set and enforce a fixed environmental capacity budget for port areas with integrated limits on land use, emissions, nitrogen deposition, biodiversity impact and water use

Prioritise Conservation to Protect Existing Biodiversity:
Prioritise conservation over restoration by directing funding to protect existing biodiversity, maintain minimum viable populations, ensure habitat connectivity, and support the interdependent systems that healthy ecosystems rely on.

Minimise the Need for Physical Expansion:
Reduce pressure for additional land development by improving efficiency, digitalisation, dematerialisation, and by phasing out harmful port or tenant activities where possible.

Adopt a "No New Virgin Capacity" Approach for New Projects:
Where expansion is unavoidable, consider alternative sites or innovative solutions (e.g., floating or vertical infrastructure) to avoid Natura 2000 and other sensitive ecosystems.

Create a legally protected environmental compensation fund:
Ensure that the fund is capitalised before construction begins.

Address global biodiversity impacts of trade:
Require biodiversity-footprint disclosure and reduced reliance on commodities linked to deforestation. Ensure strong enforcement of the EU Deforestation-Free Products Regulation and alignment with the Corporate Sustainability Due Diligence Directive.

Promote Integrated Multi-Use Spatial Solutions:
Support integrated, multi-use spatial solutions that deliver ecological and economic co-benefits, building on the Netherlands' engineering capabilities (for example by combining port functions with nature restoration, renewable energy and climate adaptation).

Incentivise Business Models Aligned With Planetary Boundaries:
Encourage business models that prioritise long-term ecological and social value over continuous expansion, rewarding organisations operating within planetary boundaries (such as stewardship-ownership models already operationalised in the Netherlands).

Embed Ecological Considerations in Governance:
Give ecological interests formal weight in governance by incorporating non-human life into decision-making, for example through frameworks such as the Zoöp model developed at Het Nieuwe Instituut in Rotterdam.

Conclusion and Call to Action

The accelerating decline in biosphere integrity represents one of the most urgent and existential planetary crises of our time. In the Netherlands, this is not a distant or abstract problem: it is a lived reality, with ecosystems collapsing in real time after decades of intensive exploitation and land transformation. The country stands at a critical crossroads, balancing economic ambitions with a moral and ecological imperative to protect some of Europe's most sensitive and irreplaceable natural systems.

As this analysis demonstrates, biodiversity loss is not just an environmental concern; it is a profound threat to legal stability, economic continuity, public health, and social cohesion. Left unaddressed, it risks entrenching irreversible damage that no amount of technological innovation or financial compensation can undo.

This moment calls for radical course correction. It requires rethinking development from the ground up, shifting from extractive, linear models towards regenerative, nature-positive, and circular systems. It means phasing out harmful activities rather than simply offsetting them, redefining "growth" in terms of ecological health and collective well-being rather than throughput and land expansion.

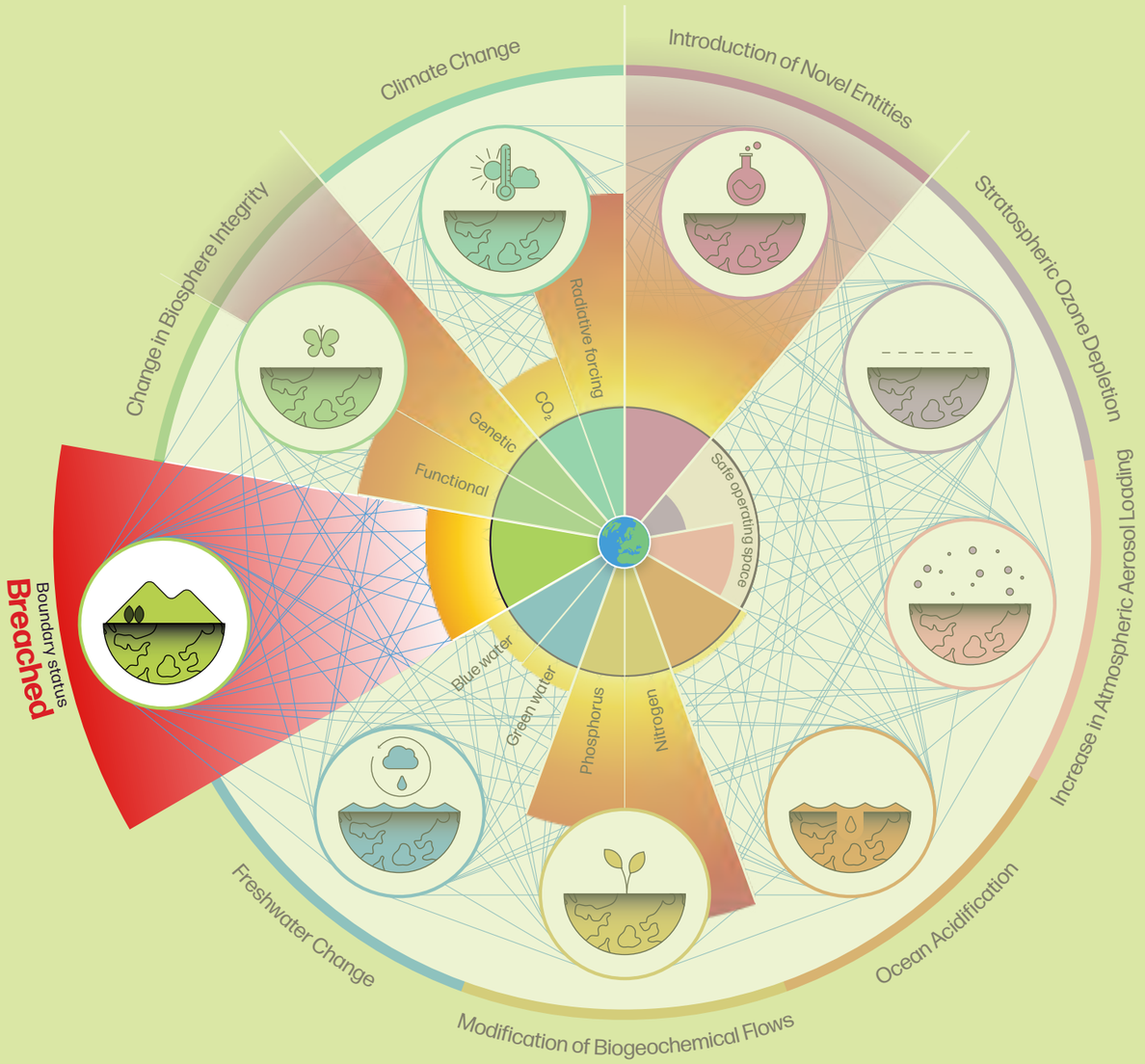
Biodiversity protection is not a constraint on progress; it is an invitation to reimagine what true prosperity means. By embracing proactive, systemic stewardship backed by robust legal frameworks, visionary planning, and adequate, front-loaded investment in conservation, the Netherlands can lead Europe and the world in showing that economic and social resilience are inseparable from ecological integrity. The choice is clear: radical regeneration today or risk triggering cascading tipping points of collapse. There is still time, but it is rapidly running out.

Innovations in governance models, e.g., stewardship-ownership, demonstrate that it is possible to embed the rights and needs of non-human life into the heart of economic decision-making, turning ports and other infrastructure hubs into true stewards of life rather than extractive zones.

As a major global trading hub and top importer of high-impact commodities, the Netherlands also holds co-responsibility for biodiversity loss well beyond its borders. True leadership requires reducing these externalised impacts and progressively aligning the Netherlands' economic footprint with ecological integrity across global supply chains.

"It is that range of biodiversity that we must care for – the whole thing – rather than just one or two stars."
David Attenborough

CH4 Land System Change



CH2 Climate Change
CH3 Change in Biosphere Integrity
CH4 Land System Change
CH5 Freshwater Change
CH6 Modification of Biogeochemical Flows
CH7 Ocean Acidification
CH8 Increase in Atmospheric Aerosol Loading
CH9 Stratospheric Ozone Depletion
CH10 Introduction of Novel Entities

Figure 4.1 Planetary Health Check 2025 status: Land System Change

Source. *Planetary Healthcheck 2025*. CC BY 4.0.

Introduction to the Boundary (Global)

Land System Change refers to the human-driven transformation of natural landscapes for different purposes – transforming forests into farmland, grasslands into urban areas, wetlands into industrial sites, or coastal areas into ports and infrastructure, or changing how existing land is used, such as shifting from sustainable farming to intensive agriculture, mining, or changing forest management practices. These changes reduce the capacity of the earth to absorb and store greenhouse gases such as carbon dioxide, methane, and nitrous oxide, recycle moisture, and support diverse living organisms.

The land use change boundary uses global reduction in forest area as its indicator. The boundary for forest cover is set at 75% of the original (pre-industrial) forest extent (circa 1700), with safe levels specified for different types of forests: 85% for boreal and tropical forests, and 50% for temperate forests. The global forest extent in 2025 was estimated at 59% of its original pre-industrial coverage (based primarily on satellite-derived data) well below the 75% boundary[251].

As a result of direct land-use change and, increasingly, indirect impacts of climate change (such as fires, pests, and drought), global and regional forests have been steadily declining over the last few decades across all major forest types. Most major forest regions have already lost so much forest cover that they are operating far outside their safe planetary boundaries, putting their resilience and ecosystem functions at serious risk. In some regions including temperate and tropical America, forest cover was previously within the safe boundary, but recent deforestation has pushed them beyond it[252]. Forestry practices and agriculture are some of the main drivers of global deforestation[253].

Even if some improvement has already been made in the past years, the annual global deforestation rate remains too high, reaching 6.6 million hectares in 2022[254], per year at last count, which is an area about the size of Ireland[255]. The world is not on track to meet its international forest pledge 2030 target[256] according to the Forest Declaration Assessment, where the deforestation rate would need to fall to zero.

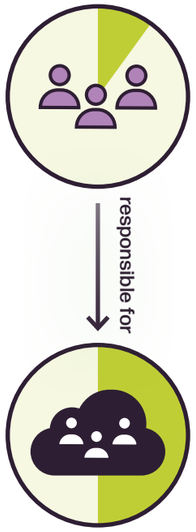
A recent Chatham House[257] report warns of serious negative impacts if land use change is not appropriately addressed:

Resource security crises and conflict: Intensifying competition for scarce productive land will drive a "scramble for resources" where powerful nations exploit weaker countries' land through economic pressure or direct appropriation. This breakdown in international cooperation will undermine global efforts to address environmental challenges and increase the risk of territorial conflicts over fertile land, water sources, and strategic resources[258].

Collapse of essential life support systems: Continued land degradation will fundamentally undermine the natural systems that sustain human civilisation including forests that stabilize the climate and regulate rainfall, freshwater systems that ensure clean water and protect against drought and floods, soils that maintain fertility and support food production, and biodiversity systems that enable pollination, pest control, and genetic resilience. Under a business-as-usual scenario, with current dietary trends and industrial agriculture practices continuing, food security will be threatened by a projected shortfall of up to 573 million hectares of productive farmland by 2050, nearly twice the size of India[259]. This deficit arises because degraded, urbanized, or otherwise converted land will no longer be available to grow enough food to meet current global consumption trajectories. Freshwater availability will decline as forests that recycle moisture, regulate rainfall, and stabilize water flows are destroyed. Climate stability will deteriorate as forests and other carbon-storing ecosystems are converted, while Biodiversity loss eliminates the species and ecological functions, such as pollination, nutrient cycling, and pest control, that help ecosystems remain stable and resilient, ultimately undermining the services that human societies rely on for food, water, and climate regulation.

Escalating global inequality and injustice: The land crunch will disproportionately impact the world's most vulnerable populations while enabling wealthy nations to secure resources at others' expense[260]. Developing countries with weak governance will face land exploitation by more powerful states and corporations, while "land-poor developing countries" will suffer most from trade disruptions and resource shortages. Contrary to persistent but misleading narratives that blame overpopulation, it is not the world's poor, nor population numbers alone, that drive unsustainable land use and environmental breakdown. Excessive consumption patterns[261] affluent groups, particularly middle- and high-income individuals in wealthy nations, lie at the heart of land system pressures and material extraction. Recent analyses show that the wealthiest 10% of the global population alone is responsible for nearly half of global emissions in 2019[262,263] and a disproportionate share of resource use, including land[264]. This dynamic entrenches systemic injustice, forcing those least responsible for environmental degradation to suffer the harshest consequences and undermining global efforts towards equity and sustainability.

In 2019, the
10%
wealthiest of the global population



~50%
of the global emissions in 2019.

Land System Change is one of the most interconnected boundaries, with particularly strong relationships to:

Climate Change: Natural causes of tree cover loss, like wildfires and desertification, have intensified due to climate change, leaving a worrying scenario for such vital ecosystems[265]. In 2024, around 30 million hectares of tree cover were lost worldwide (roughly the size of Italy), the largest area since 2001. In 2024, wildfires were the main driver of global deforestation, accounting for nearly 14 million hectares of tree cover loss, roughly half of the total area lost worldwide that year, making it the worst year since the turn of the century[266]. Deforestation accounts for about 10% of all human-induced greenhouse gas emissions each year. Deforestation also reduces the number of trees available on earth to absorb carbon dioxide in the air, worsening the problem and accelerating climate change[267].

Biosphere Integrity: Deforestation causes habitat loss, habitat fragmentation, and increased human-wildlife conflict. When forests are cleared, countless species lose their homes and the resources they need to survive, leading to severe population declines and frequent local extinctions, and, in some cases, global extinction. Habitat fragmentation divides continuous forests into smaller, isolated patches, which can limit species' movement, reduce genetic diversity, and disrupt breeding patterns. As human activities trespass on natural habitats, the likelihood of human-wildlife conflict increases, often resulting in harm to both animals and humans[268].

Freshwater Change: Large-scale deforestation significantly reduces freshwater availability through complex forest-climate interactions. Deforestation reduces local and downwind rainfall through decreased moisture recycling, with this effect being particularly strong in tropical regions like the Amazon and the Congo where rainfall largely relies on local evaporation from forests[269]. While deforestation directly increases water runoff by reducing evaporation from trees, this positive effect is largely cancelled out by the negative impacts of reduced rainfall, resulting in a net reduction in freshwater availability. A recent study demonstrates that climate feedback effects from deforestation can reduce water runoff by 6.2 ± 3.6 mm/year globally[270]. While 6.2 mm per year may sound small, when considered globally, this reduction represents a significant loss of freshwater resources. The yearly precipitation averaged over the whole Earth is about 1000 mm (39 inches), but this is distributed very unevenly[271]. Losing ~ 6.2mm globally means some regions are losing the equivalent of weeks or months of their normal water supply, which can be devastating for local communities (drinking water supplies and agriculture use) and ecosystem health.

Modification of Biogeochemical Flows: Research on nutrient cycling in Costa Rica showed that deforestation led to a 95% increase in dissolved nitrogen loss to water systems and a 33% loss of soil phosphorus. This is attributed to the loss of vegetation, which normally helps prevent run-off and soil erosion[272].

National Context: The Netherlands

In the Netherlands, land-use governance is a highly structured multi-tiered system. The Environment and Planning Act[273] ("Omgevingswet"), effective 1 January 2024, consolidated 26 laws and around 150 regulations[274] into one unified planning and environmental statute[275]. It also streamlined permitting through a single online portal with accelerated processing compared to previous standards[276].

The Dutch state focuses on subjects that are of importance to the entire country, such as improving accessibility. These national interests are set down in the Vision on Infrastructure & Spatial Planning[277] (SVIR). The provinces focus on provincial interests, for example, landscape management, urbanisation and the preservation of green spaces[278]. Provincial interests are set out in the provincial spatial visions. Spatial planning policy and its implementation are, in so far as possible, shaped at the municipal level. Municipalities set appropriate regulations based on their knowledge of the local situation[279].

Approximately two-thirds[280] (65%) of the Netherlands' agricultural exports consist of domestically produced goods, with the remainder being re-exports of foreign agricultural products. Although not all domestic production is exported, the Netherlands' export-oriented agricultural system externalises significant resource use. Studies show that about 89% of the Dutch water footprint is external[281], and for key sectors such as dairy, pork, and poultry, between 47% and over 90% of land use occurs abroad for feed imports[282]. This means that much of the environmental burden associated with Dutch agriculture, its embedded water, nutrient, and land use, is displaced beyond national borders, illustrating how domestic production and trade systems contribute to global land system pressures.

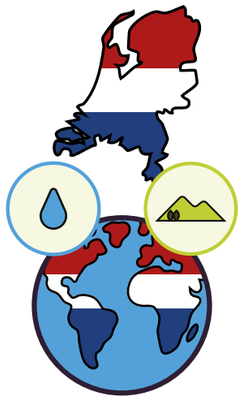
The Municipality of Rotterdam governs land-use change through a layered framework based on its Omgevingsvisie Rotterdam[283], which sets the city's long-term spatial and environmental strategy under the national Omgevingswet (Environment and Planning Act). This vision promotes "Good Growth and Connection"[284] by guiding densification, climate adaptation, urban greening, and inclusive development across five spatial perspectives that form **a compass for guiding good growth:**

- **compact** (promotes densification rather than urban sprawl), **healthy** (designs the city to promote physical and mental health),
- **sustainable** (climate adaptation and mitigation),
- **productive** (supports a diverse economy), and
- **inclusive** (ensures that spatial and social development benefits all residents)[285].

The Bestemmingsplannen (zoning plans) provide area-level regulations that control land-use functions and development permissions[286]. Rotterdam's annual Grondbeleid (Land Policy Report)[287] outlines its active role in land acquisition, preparation, and public-private partnerships to steer land development towards strategic goals. The "Een Stad"[288] agreement, a four-party pact between Leefbaar Rotterdam, VVD, D66, and Denk, focuses execution and practical, citizen-centered governance.

The Port of Rotterdam, Europe's largest seaport, is governed through a separate but closely linked spatial framework, the NOVEX Rotterdamsehaven[289] (2025 – 2050), which is coordinated with the municipality and national government, balancing logistics expansion with energy transition, climate resilience, and industrial redevelopment.

While these frameworks exist at national, provincial and municipality level, it is unclear how these layers are integrated in practice. While the law aims to streamline spatial governance, it often fails to resolve persistent coordination gaps between levels of government, and lacks enforceable mechanisms (e.g., binding national targets with subnational quotas, conditional funding or grants, independent oversight bodies, etc.) to align long-term transport, environmental, and spatial objectives (including in Rotterdam)[290].



Much of the environmental burden associated with Dutch agriculture, including its embedded water, nutrient, and land use impacts, is displaced beyond national borders.

A Council for the Environment and Infrastructure (Rli)[291] analysis identified 5 key factors impeding policy for the physical living environment in the Netherlands:

- Accumulation, and hence complexity, of policy;
- Hesitancy about taking the necessary steps;
- Inadequate organisation of implementation;
- Unequal distribution of costs and benefits;
- Structural scarcity of human resources.

Direct Impacts of Shipping and Ports: Drivers and Consequences

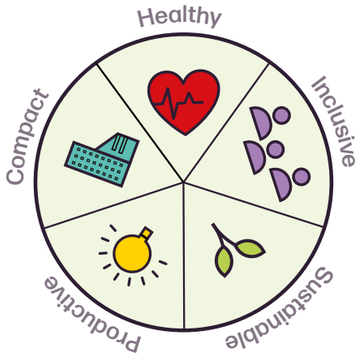
Ports are powerful catalysts of land use change, reshaping coastal and urban geographies in ways that are often irreversible. Their influence extends well beyond the shoreline, linking global maritime trade to local patterns of development, environmental degradation, and urban restructuring. Construction and expansion of ports lead to significant changes in land use, often through large-scale reclamation projects that convert environmentally sensitive wetlands, mangroves, tidal areas or agricultural zones, and floodplains, into terminals, logistics parks, and industrial zones. Between 2000 and 2018, port areas in Europe grew by 12.5%[292].

The intensification of shipping activity increases the use of land to support logistics functions such as warehouses, rail yards, and container depots, resulting in the transformation of peri-urban (transitional areas between the urban core and rural countryside) and rural land into commercial and industrial zones. This development often fragments existing landscapes and ecosystems, reducing biodiversity and the quality of life- and civilisation-supporting functions.

In parallel, sustainability initiatives, such as the development of circular economy zones, green hydrogen production sites, and low-emission logistics clusters, are placing new demands on land. While these projects aim to reduce environmental impact, they often require additional space, complicating land-use dynamics in and around ports[293]. Moreover, as circular initiatives expand, more manufacturing and processing will occur locally, further increasing competition for available space.

The maritime industry's increasing demand for biofuels[294] creates pressures on global land systems[295] as large-scale biofuel production often requires significant land conversion from food production or natural ecosystems to energy crops[296]. As many biofuel production facilities are already operational, these are likely to be the first alternative that shipowners turn to for compliance with GHG regulations[297]. The cropland required to meet shipping's biofuel demand in 2030 could range from 33 to 40 million hectares based on a T&E estimate[298], making it crucial that this transition does not simply shift environmental impacts from carbon emissions to land degradation.

Rotterdam's long-term spatial and environmental strategy of 'Good Growth and Connection'



Solutions and Maritime Interventions

UN Convention to Combat Desertification (UNCCD): Established in 1994 to protect and restore land and ensure a safer, more just, and sustainable future, the UNCCD is the only legally binding framework dedicated to addressing desertification, land degradation, and the effects of drought[299]. There are 197 Parties to the Convention, including 196 countries and the EU[300].

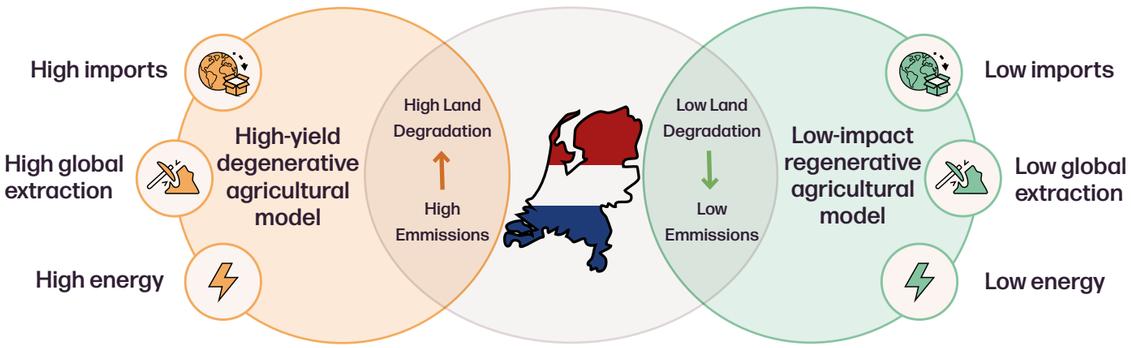
A central goal of the UNCCD is to support countries in achieving Land Degradation Neutrality (LDN)[301*], a concept that aims to maintain or increase the amount and quality of productive land resources by balancing new land degradation with restoration efforts. In practice, this means that any land degraded through human activities is offset by restoring an equivalent amount of land elsewhere, keeping the overall land base stable or improving it.

As a Party to the UNCCD, the Netherlands is committed to reporting on land degradation and working towards the Convention's objectives. However, it has not set a formal quantitative national LDN target under the UNCCD framework[302]. Nevertheless, the Netherlands has begun implementing measures to address domestic land degradation, including initiatives focused on peatland restoration, soil health, and biodiversity recovery. These efforts are early but essential steps towards improving resilience in a landscape heavily used for agriculture and livestock. While these efforts represent meaningful progress and demonstrate leadership in land stewardship, much work remains to fully reverse degradation trends and ensure long-term ecological resilience. Sustained commitment and scaled-up action will be essential to truly achieve land degradation neutrality and secure a healthy, productive landscape for future generations.

Transforming food systems: Shifting towards more plant-forward diets[303] can drastically reduce land use by cutting the need for grazing land and croplands dedicated to animal feed[304]. If the entire world adopted a plant-based diet, global agricultural land use could shrink from 4 billion to just 1 billion hectares[305]. This is equivalent to the entire land area of Africa. Additionally, more than 1 billion tonnes of food, equivalent to 24% of all calories produced globally is lost or wasted between farm and fork[306]. The land footprint of this wasted food is roughly equivalent to the entire land area of China.

These transformations are directly relevant to port systems such as Rotterdam's, which play a central role in the import, processing, and distribution of agricultural commodities, animal feed, and agrochemical inputs such as synthetic fertilisers and pesticides that underpin intensive production. The Netherlands' high-yield agricultural model depends on these imported materials, tying its land-use footprint to global extraction and energy systems. Reducing reliance on imported feed crops and fertilisers, and promoting sustainable, low-impact food supply chains, would not only lower shipping-related emissions and land degradation abroad but also reduce domestic nutrient surpluses and pollution. By facilitating circular and regional food logistics, such as shorter supply chains, alternative protein processing, nutrient recycling, and reuse of organic waste streams, the port can become an enabler of land-use efficiency and regenerative food systems.Alongside dietary changes and food waste reduction, improving the productivity of land use, such as by making grazing lands more efficient or sustainably increasing crop yields, would allow us to produce more food with less land[307], reducing pressure on ecosystems and enabling land to be restored or repurposed for nature. Transforming the global food system is expected to cost substantially less than the hidden costs of the current food system, of which externalised health impacts make up the major share[308, 309].

By facilitating circular and regional food logistics, such as shorter supply chains, alternative protein processing, nutrient recycling, and reuse of organic waste streams, the port can become an enabler of land-use efficiency and regenerative food systems.



Promoting agroforestry and nature-based solutions: Agroforestry (the practice of integrating trees into farms and pastures) alone has the potential to increase food security for 1.3 billion people, while investments in agriculture, mangrove protection and water management will help adapt to climate change, with benefits around four times the original investment[310].

Vertical farming can use up to 28 times less land than traditional farming methods for certain crops, but it requires significant energy inputs. To ensure it truly supports environmental goals rather than undermining them, it must be paired with renewable energy, efficient electricity use, and sustainable emissions and waste management[311].

For ports such as Rotterdam, nature-based solutions are directly relevant to both land and water management. Agroforestry and wetland restoration in upstream catchments can reduce sedimentation, nutrient runoff, and flood risk affecting port operations, while within the port area, green buffers, living shorelines, and vegetated logistics zones can enhance biodiversity and climate resilience. Moreover, ports like Rotterdam are critical nodes in global agricultural commodity flows. While ports don't control upstream sourcing decisions, they can influence supply chains through sustainability criteria for port tenants, partnerships with certification bodies to verify shipments, and investment in traceability systems, creating market signals that can favour regenerative land use practices.

Minimise reliance on land-intensive technologies: As we transition to a low-greenhouse gas economy, it is crucial to avoid over-dependence on land-intensive solutions such as bioenergy with carbon capture and storage (BECCS). BECCS can require up to 1,000 times more land than fossil fuel alternatives, and 40–50 times more land than solar photovoltaics[312], making it extremely land hungry. If policymakers rely heavily on bioenergy and BECCS to achieve net-zero targets by 2050, the area of agricultural land needed for energy crops could exceed 20% of current global cropland[313], threatening food security and biodiversity. While BECCS is sometimes included in climate scenarios as a theoretical carbon removal option, it is widely considered unfeasible at scale and should not be relied upon as a primary strategy. Instead, direct emissions reductions, nature-based solutions, and energy efficiency must remain the core focus of climate action.

Improve monitoring and accountability: Developing consistent measurement, reporting, and verification frameworks covering all land uses globally will enable countries to adequately assess the risks of land degradation, weigh up the relative merits of different land-use policies, and drive change accordingly[314]. Expanding corporate disclosure requirements for land-use impacts and nature-related risks will enable us to measure collective progress and identify areas where urgent intervention is required[315]. Mandatory disclosure forces companies to assess and report their actual land footprint, creating pressure to reduce harmful impacts throughout their supply chains. This would also curb greenwashing and the proliferation of ineffective solutions.

Incentivising circular economic practices: such as recycling, reusing products, and extending their lifespans, reduces the need for new raw materials and minimizes waste. By lowering primary resource demand, these practices significantly reduce pressure on land resources[316] that would otherwise be used for mining, agriculture, and waste disposal.

* LND is "a state in which the quantity and quality of land resources, necessary to support ecosystem functions and services and enhance food security, remain stable or increase within specified temporal and spatial scales and ecosystems."
https://www.cariassociation.org/wp-content/uploads/2023/09/Da22_Note_Neutrality_EN.pdf

Restoration and reforestation efforts: While reforestation remains an important climate change mitigation strategy, new research shows that the actual area suitable for reforestation is far smaller than once believed. When environmental and social safeguards are applied to avoid harming native grasslands, savannas, and other biodiverse ecosystems, the realistic area available for new forest planting is 71–92% smaller than earlier optimistic global estimates—meaning only 8–29% of those original estimates remain viable. This highlights that large-scale tree planting is not a one-size-fits-all solution for all 'open' areas[317] and must be carefully targeted to the right locations. Reforestation efforts should complement, rather than replace, the urgent need to protect existing natural ecosystems and reduce emissions at the source.

Current Contributions and Facts from the Port of Rotterdam

The Port of Rotterdam's influence on land use extends far beyond its physical boundaries. While land within the port area is allocated to logistics, industry, and emerging energy activities such as biofuel and hydrogen production, the port's economic ecosystem drives significant indirect land-use impacts worldwide through the trade it facilitates. Agricultural commodities, fossil fuels, fertilisers, and biomass shipped via Rotterdam are directly linked to land conversion and resource extraction across global supply chains. Recognising these indirect effects is essential to understanding Rotterdam's total land-use footprint and to designing interventions that address both the port's direct and systemic impacts.

The Port of Rotterdam is the largest seaport in Europe, stretching 42 kilometers in length and 10 kilometers in width. It covers 12,500 hectares of land and water. Over 6,000 hectares are dedicated to industrial use such as refineries, storage facilities, and chemical plants. Each year, the port handles approximately 28,000 seagoing vessels and 91,000 inland vessels, with an annual freight throughput of about 436 million tonnes[318] serving as a critical gateway connecting Europe to global trade networks.

The port has undergone numerous transformations since Rotterdam's origins in 1270, when a dam was built across the river Rotte to protect the settlement from flooding. In 1340, this small fishing village was granted city rights, setting the stage for rapid growth. In the 16th century, the booming herring trade with the Rhine-Schelde region and France turned Rotterdam into a thriving commercial hub. Trade with England, Scotland, and France continued to fuel its expansion, and by 1618, wine had become the city's primary import commodity. Between 1650 and 1850, Rotterdam's urban landscape was shaped by largely unstructured growth and the development of the 'Waterstad' (Water City)[319], a district closely tied to its evolving maritime character.

The Industrial Revolution brought a significant shift in Rotterdam's commodity profile and infrastructure. By the late 19th century, the port had become a crucial transit hub for heavy industrial goods such as ores, industrial chemicals, and machinery. Rhine barges carried steel, iron, cereals (used for food and animal feed), and oil, which together accounted for about 74% of total trade in 1913. Meanwhile, coal, primarily sourced from Germany's Ruhr region, made up the bulk of transport activity, with Rotterdam serving as a crucial transit hub for distributing German coal to other markets. The construction of the Nieuwe Waterweg, the direct, straight, connection to the North Sea, then kicked off a new stage in the port city's development. This was followed by the development of docks like Rijnhaven, Maashaven and Waalhaven (Rhine, Meuse and Waal docks) on the southern bank[320].

The port's new strategy now states that it emphasises circular use of space, greater efficiency, multifunctionality, and resilience instead of relying on new land reclamation.

In the post-World War II era, oil emerged as Rotterdam's most important bulk commodity, accounting for 58% of total throughput by 1963. The construction of the Europoort, which began in the late 1950's, transformed the port, creating a vast 25,000-acre (10,000-hectare) industrial and port area, fifty times larger than it had been in 1880. By 1962, Rotterdam had become the world's largest port[321], a title it would hold for decades. In the following years, the rise of container shipping fueled further growth. The Maasvlakte 2 expansion (2008 – 2012) reclaimed 2,000 hectares of land from the sea, significantly increasing capacity and enabling the port to potentially double its container transhipment volumes[322].

With growing environmental pressures, including climate risks like sea-level rise, biodiversity loss, and stricter greenhouse gas (GHG) reduction targets, combined with the need for climate adaptation, energy transition, and inclusive urban development, the Port of Rotterdam must evolve qualitatively rather than expand endlessly outward. The port's strategy now emphasises circular use of space, greater efficiency, multifunctionality, and resilience instead of relying on new land reclamation[323]. Although proposals for Maasvlakte 3 occasionally resurface as a potential future expansion to accommodate extra container capacity, energy hubs (such as hydrogen), or industrial growth, no formal decision has been made. Recent discussions have highlighted competing visions for how the port should balance its future role, with port development advocates emphasizing economic growth and enhanced logistical capacity, while environmental organisations stress the need for ecological preservation and fulfillment of prior environmental compensation commitments[324].

This reflects a broader shift in thinking: future port development must respect planetary boundaries and integrate more closely with ecological and urban systems. Achieving this transition will require clear implementation plans, sufficient resources, and strong robust governance and accountability mechanisms[325] to ensure lasting impact.

Recommendations for the Port of Rotterdam

- **Implement circular land use principles:**
  Accelerate the utilisation of multi-functional zones that integrate logistics, energy transition infrastructure, and nature-based solutions within existing boundaries based on the NOVEX Rotterdamsehaven plans. Evaluate, pilot and implement automated vertical storage systems and multi-storey logistics facilities to maximise cargo handling capacity without new land reclamation. Continuously optimise vessel scheduling to reduce vessel waiting times and minimise spatial and emissions footprints.

- **Establish land stewardship commitments:**
  Develop land impact compensation requirements aligned with Dutch and EU nature restoration and biodiversity obligations. Restoration efforts should specifically address ecological functions lost due to expansion, such as wetland flood protection, fish nurseries, and habitats for pollinators and birds, to ensure truly functional offsets. Establish a dedicated land stewardship fund, financed through port fees and environmental levies on land-intensive activities.

- **Promote circular and regenerative economy zones:**
  Designate and prioritise areas for circular and regenerative (restoring and improving ecosystems) industry clusters, focused on reducing reliance on primary resources (using fewer raw virgin materials) and lowering land and emissions pressures. Provide spatial and policy support to steward-owned and sufficiency-oriented enterprises that integrate ecological limits, societal well-being, and clean port job creation at their core. For example, bioplastics manufacturers replacing fossil plastics, or a cargo shipping company operating with a governance model that actively regenerates marine and coastal ecosystems as part of its mission. Encourage industrial symbiosis by linking waste and resource flows between firms, and promote on-site recycling and remanufacturing to further reduce transport-related land impacts.

- **Enhance and restore urban green buffer zones:**
  Located around and within the port, including tidal wetlands, salt marshes, coastal dunes, vegetated stormwater corridors, and pollinator meadows, to improve local ecosystem functions, filter runoff, mitigate heat effects, and provide biodiversity connectivity within heavily industrialised landscapes.

- **Promote sustainable marine fuels and supply chain integrity:**
  Prioritise biofuel suppliers and bunkering facilities that demonstrate robust certification and traceability systems, avoiding high-ILUC (Indirect Land Use Change) crop-based biofuels derived from palm oil, soy, rapeseed, and corn in favour of low-ILUC alternatives such as waste oils, used cooking oil, agricultural residues, algae, and advanced synthetic fuels. Implement port-level verification procedures for sustainability certificates and require digital traceability documentation from feedstock origin for all biofuel deliveries.

- **Incentivise sustainable marine fuels through preferential access:**
  Establish preferential berthing, bunkering access, or fee structures that incentivise vessels using certified low-ILUC biofuels or green synthetic fuels over food crop-based alternatives. Collaborate with fuel suppliers, certification bodies, and enforcement authorities to detect and prevent fraudulent sustainability claims, supporting development of blockchain-based or other tamper-proof tracking systems for biofuels handled through Rotterdam facilities

The Port of Rotterdam

Designate and prioritise areas for circular and regenerative (restoring and improving ecosystems) industry clusters, focused on reducing reliance on primary resources (using fewer raw virgin materials) and lowering land and emissions pressures.

Regenerative clean cluster pilot zone: Renewable energy

Recommendations for Policymakers

- **Expand monitoring efforts:**
  Implement environmental and lifecycle analysis monitoring and certification schemes for cargo to account for the complete land-use impacts embedded in goods passing through the port. Pilot enhanced and accelerated disclosure requirements for land use impacts across entire value chains of companies operating in the port area, serving as a model for future EU regulations.

- **Consider supply chain efforts:**
  Strengthen the Netherlands' commitment to international land restoration financing, particularly in developing countries where Dutch imports and consumption contribute to land degradation, such as soy and palm oil from South America and Southeast Asia, cocoa from West Africa, and tropical timber from vulnerable forest regions.

- **Strengthen innovation and collaboration:**
  Increase research and development funding for land-efficient technologies and practices, for example, agroforestry, vertical farming, multi-storey logistics systems. Establish innovation hubs that unite researchers, businesses, and communities to co-create practical solutions. Embed these hubs within governance frameworks that balance economic sufficiency objectives with sustainability targets, circular economy principles, and measurable environmental and social outcomes, ensuring public oversight and adherence to strict sustainability criteria.

- **Develop and mandate social justice frameworks:**
  Design and formalize a robust social justice framework to guide The Port of Rotterdam. This framework should include criteria for fair distribution of benefits and burdens, global supply chain responsibility, and meaningful inclusion of impacted communities, both locally and internationally. Policymakers should ensure this framework is legally enforceable and provide resources and oversight to enable effective implementation by The Port of Rotterdam. This framework should be binding not only for the port authority but also for all businesses and operators leasing or using port space, as well as for all vessels calling at the port. This would build on and improve the EU framework for corporate responsibility and due diligence, e.g., the CSDDD, and make it fit for purpose..

- **Regulate biogenic marine fuels to prevent land system impacts:**
  Support IMO adoption of sustainability criteria aligned with EU RED frameworks that exclude high-ILUC crop-based biofuels from compliance under MARPOL Annex VI regulations. Advocate for assigning quantifiable ILUC emission factors or applying fossil fuel equivalency penalties to food crop-based biofuels. Establish incentive mechanisms that prioritise scalable green e-fuels over limited waste-based biofuels, and support stringent zero and near-zero emission fuel definitions[326].

- **Strengthen biofuel certification and enforcement mechanisms:**
  Support development of tamper-proof certification systems that can track biofuel characteristics throughout complex international supply chains. Establish coordinated enforcement mechanisms between flag states, port states, and fuel suppliers to verify sustainability claims, with penalties for fraudulent certification that undermine both climate goals and land protection efforts. Ensure certification schemes include regular auditing, third-party verification, and real-time monitoring capabilities to address the documented risks of double-counting, mislabelling, and false sustainability claims in global biofuel markets[327].

Conclusion and Call to Action

The transgression of the land system change boundary, accelerated by unsustainable land management practices globally, demands urgent and transformative action.

In the maritime context, ports and shipping infrastructure present both significant challenges and remarkable opportunities for addressing land use change. The Port of Rotterdam exemplifies this duality: while the development of the port area has fundamentally transformed, and degraded one of Europe's most important delta ecosystems, it also demonstrates the potential for pioneering, regenerative approaches to maritime infrastructure if designed and governed differently.

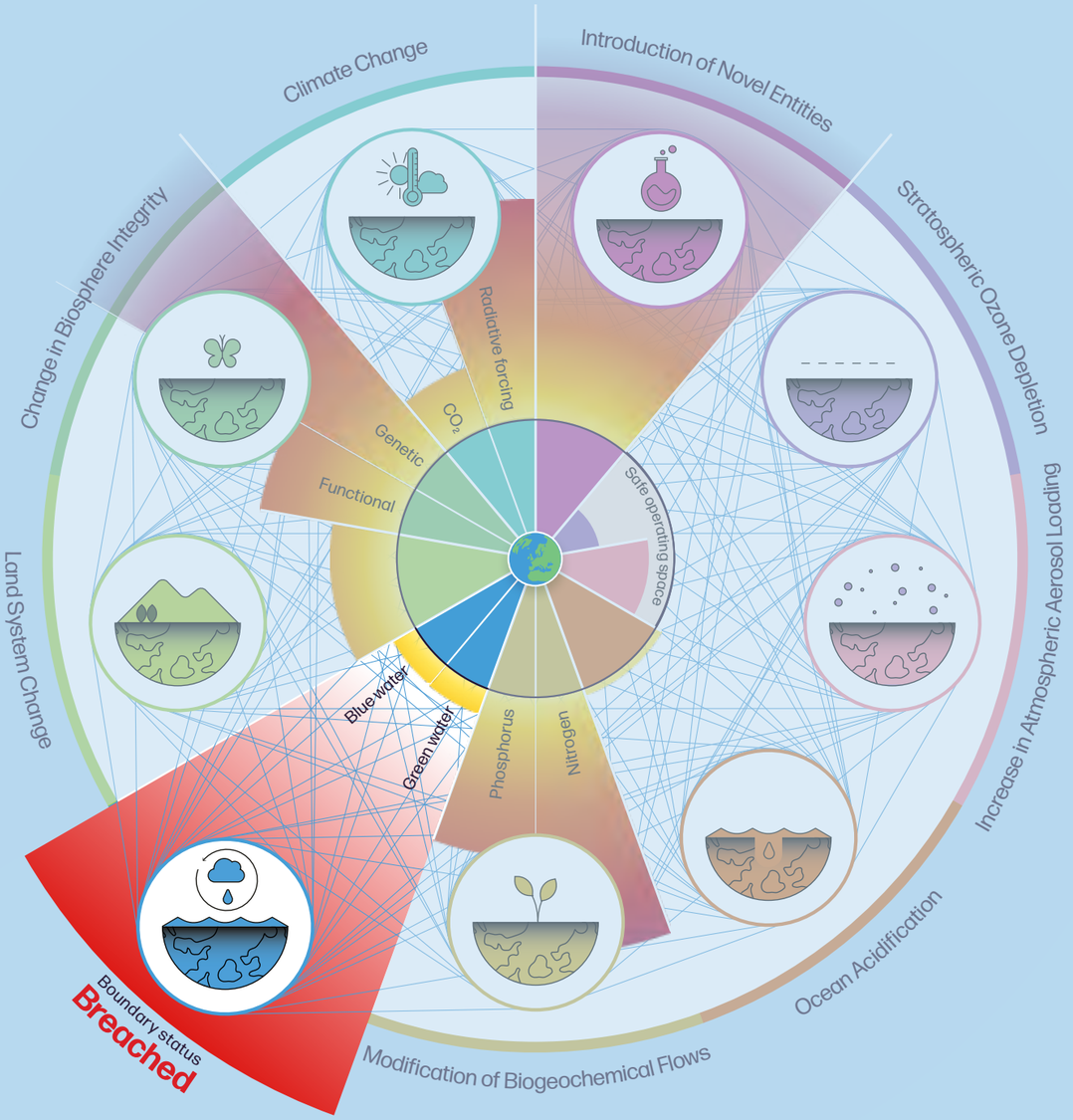
The Netherlands' sophisticated spatial planning frameworks provide a strong foundation for addressing land use change but require strengthening and better integration to meet the scale and urgency of the challenge. The current competitive pressures for scarce land resources demand more holistic, science-, and justice-based approaches to land management that rapidly contribute to achieving planetary boundary objectives.

The Port of Rotterdam has an unprecedented opportunity to become a global beacon of restorative, inclusive port development but seizing this opportunity demands bold, collective action now.

"What we are doing to the forests of the world is but a mirror reflection of what we are doing to ourselves and to one another."

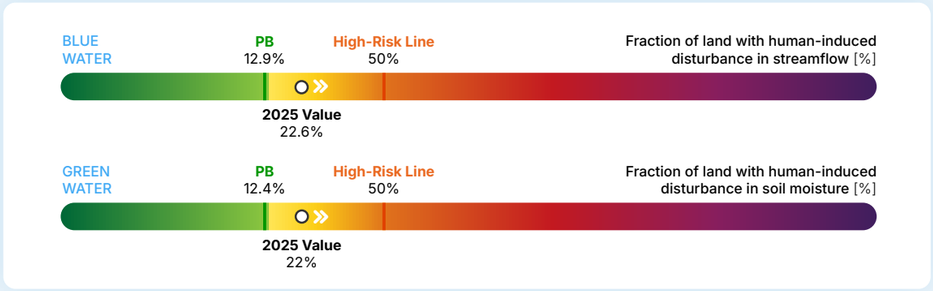
Mahatma Gandhi

CH5 Freshwater Change



CH2 Climate Change
CH3 Change in Biosphere Integrity
CH4 Land System Change
CH5 Freshwater Change
CH6 Modification of Biogeochemical Flows
CH7 Ocean Acidification
CH8 Increase in Atmospheric Aerosol Loading
CH9 Stratospheric Ozone Depletion
CH10 Novel Entities

Figure 5.1 Planetary Health Check 2025 status: Freshwater Change



Source. *Planetary Healthcheck 2025*. CC BY 4.0.

Introduction to the Boundary (Global)

The Freshwater Change planetary boundary encompasses both "blue water" (rivers, lakes, and groundwater) and "green water" (stock of soil moisture available to plants) components of the global freshwater cycle[328].

For the past century, humans have been pushing the Earth's freshwater system far beyond the stable conditions that prevailed before industrialisation. This destabilisation is driven by multiple factors, including dam construction, agriculture (particularly water-intensive farming), large-scale irrigation, urbanisation, deforestation, and climate change. As a result, exceptionally dry or wet conditions, such as droughts and floods, have become much more frequent and widespread than they were in the pre-industrial era[329].

Current status

The freshwater planetary boundary has been breached, pushing ecosystems and human societies beyond safe limits and threatening food security, water availability, biodiversity, and overall planetary stability. Scientists use two key indicators (called control variables) to measure the health of our freshwater system:

- **Human-induced disturbance of blue water** (such as rivers, lakes, and groundwater). In pre-industrial times, around 10.3% of the world's ice-free land area experienced noticeable variations in blue water flow. The safe boundary is set at 12.9%, but the 2025 value has already soared to 22.6%, nearly 1.75 times the safe limit.

- **Human-induced disturbance of green water** (soil moisture available to plants). Before industrialisation, about 9.8% of global ice-free land area showed changes in green water flow. The safe boundary is set at 12.4%; the 2025 value has jumped to 22%.

These numbers[330] show that we are approaching the high-risk territory where there's significant risk of triggering irreversible changes, and underlining just how sensitive Earth's freshwater systems are to human pressures.

Today, freshwater disruptions are already unfolding across vast regions of the world at the same time (South Asia[331], North China Plain[332, 333], Western USA[334, 335], Middle East[336] and North Africa[337], Southern Europe[338]), affecting rivers, wetlands, forests, and farmland alike. The blue water situation is especially alarming, with large-scale alterations to flow patterns undermining water availability, threatening biodiversity, and increasing the risk of floods and droughts. At these low levels, freshwater systems can no longer regulate climate, support ecosystems, or sustain human societies in a way that allows modern life to continue safely. Research published in *Nature Water* in 2024 shows that the freshwater planetary boundary was actually crossed around the mid-twentieth century, much earlier than scientists previously believed[339].

Predictable seasonal rainfall and stable river flooding patterns allowed humans to develop farming, build permanent settlements, and create cities around dependable water sources. These patterns also supported vital ecosystem services, such as climate regulation, biodiversity, and the production of food and raw materials. When freshwater cycles become unpredictable, the very foundations of how modern societies function and organise themselves around water availability are put at risk.

By 2020, 2.4 billion people already lived in countries considered water-stressed[340], meaning they withdraw 25% or more[341] of their renewable freshwater supply each year. Values below this 25% threshold are generally considered to indicate no water stress, allowing freshwater systems to replenish and continue supporting both people and nature[342]. By 2025, 1.8 billion people have been projected to face "absolute water scarcity"[343] and nearly two-thirds of the global population is expected to be living with some level of water stress[344]. This means that water insecurity is no longer a distant or future problem, it is a current and escalating global crisis that threatens health, food systems, economic stability, and geopolitical security.

Freshwater Change is closely linked to other planetary boundaries:

Climate Change influences droughts and floods by altering how much water the atmosphere can hold, changing cloud formation, and disrupting global and regional circulation patterns.

Land System Change, driven by deforestation, intensive agriculture, and urbanisation, reduces the land's capacity to hold water, alters flow in streams, and increases evaporation. This can intensify droughts and disrupt large-scale rain patterns like monsoons, creating dangerous feedback loops that further accelerate climate change.

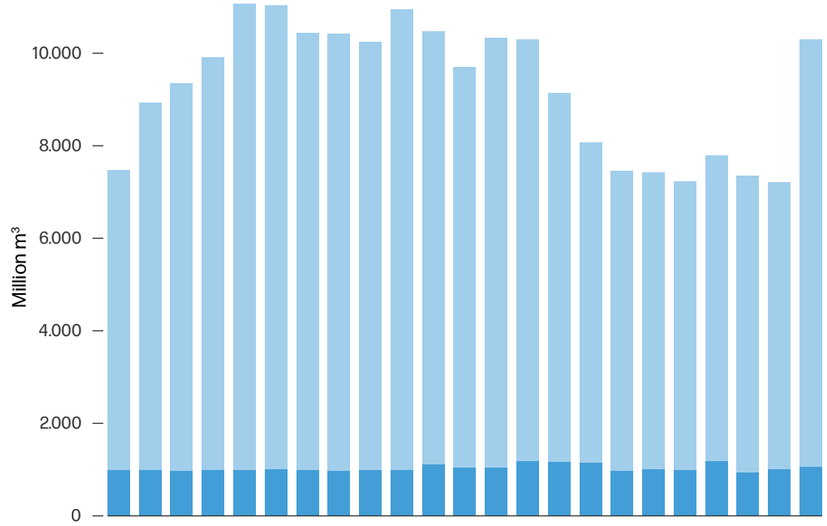
Biosphere integrity is directly threatened by decreasing freshwater availability, and by increasing droughts and floods. These shifts damage diversity, resilience and populations of organisms living in rivers, lakes, wetlands, and ponds. Vegetation and habitats along shorelines shrink or disappear as water dries up[345]. Aquatic plants, bacteria, fungi, and animals such as shellfish and fish all contribute to maintaining water quality by naturally filtering particles, breaking down organic matter, or cycling nutrients. When biodiversity declines, this self-purification capacity is significantly impaired, making freshwater systems more vulnerable to pollution and less able to recover from contamination[346].

Novel entities and nutrient overload, such as industrial chemicals, agricultural runoff, and untreated sewage, are flooding into rivers and lakes, poisoning freshwater ecosystems and undermining their ability to recover and support life. These toxic loads are pushing freshwater systems towards collapse, endangering biodiversity, and threatening human health.

National Context: Freshwater Change in the Netherlands

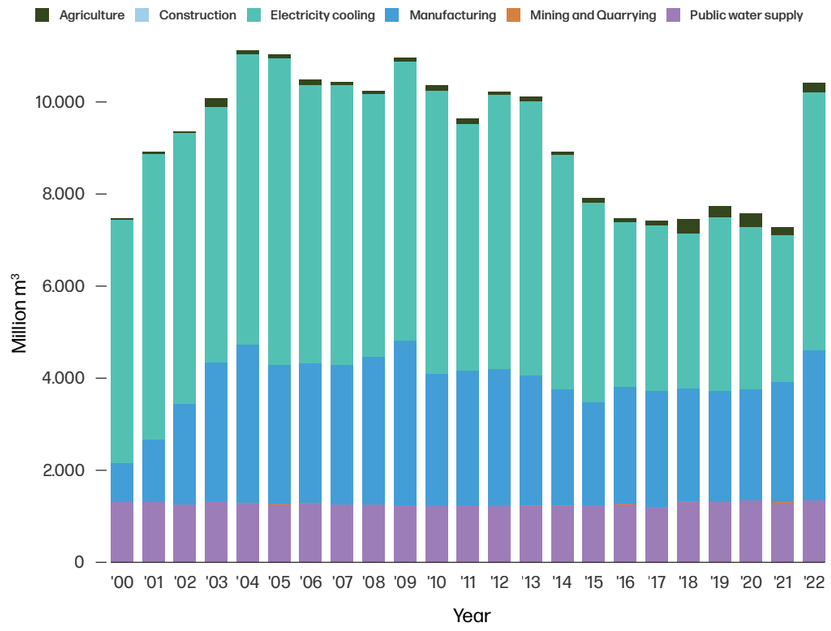
On average, Dutch households used 129 litres/day of water in 2021[347] and 119 litres/day in 2023[348]. However, according to the Water Footprint Network, the water footprint per person in the Netherlands[349] is about 4,000 litres/day, and over 95% of this is 'external', meaning it is used abroad to produce imported food, goods, and materials consumed in the Netherlands. While the Netherlands is relatively efficient in direct household water use, its total water footprint is comparable to or slightly lower than many other Western countries, reflecting the high dependence on imported products that require large amounts of water outside the country[350].

Figure 5.2 Groundwater and surface water abstraction in the Netherlands (2000–2022)



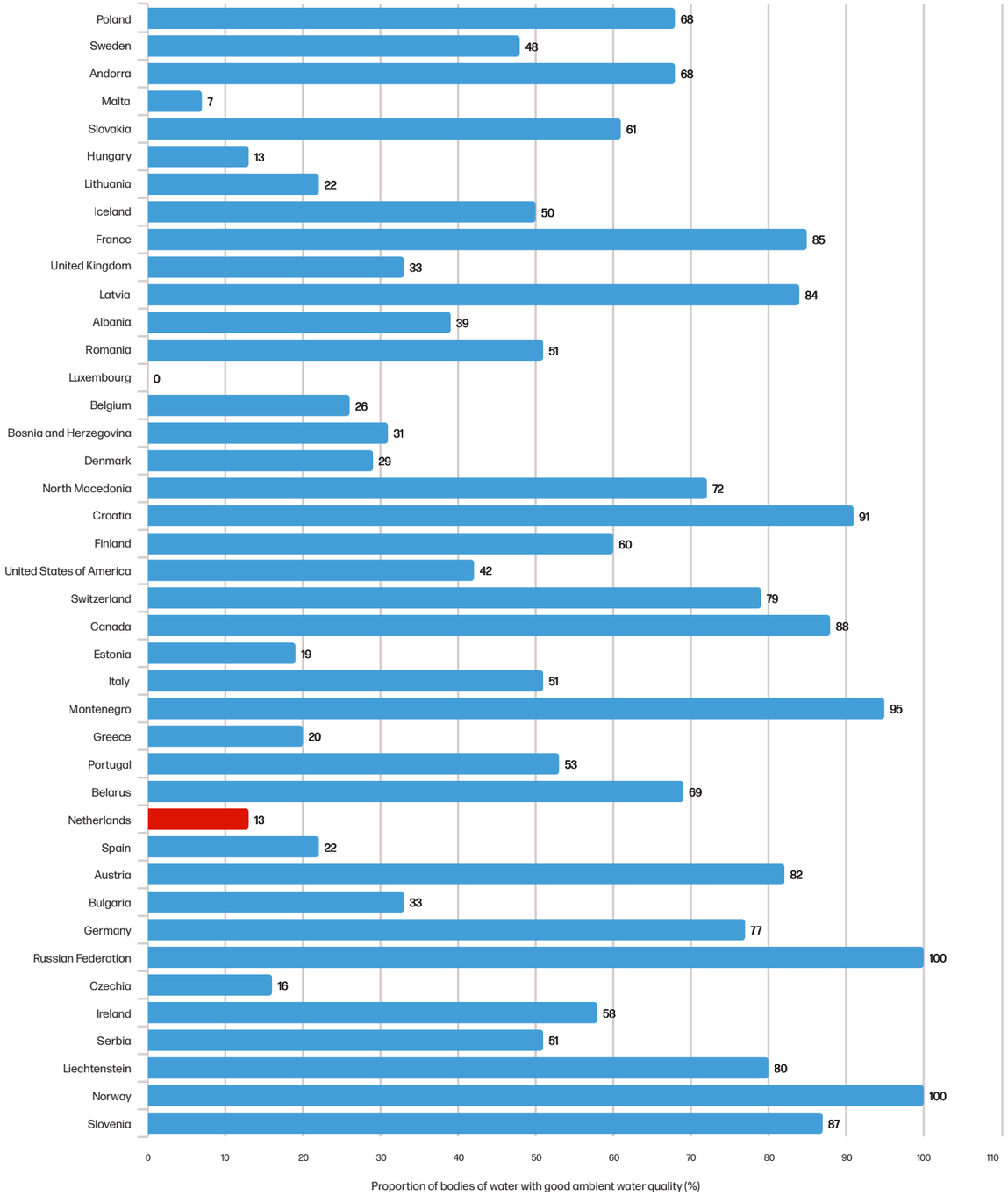
Note. This graph presents the shares of groundwater (dark blue) and surface water (light blue) in total annual water abstraction in the Eionet Member Countries, 2000-2023. Surface water contains water abstraction from rivers, reservoirs and lakes. Water abstraction for hydropower is excluded.
Source. European Environment Agency (2024), *Water abstraction by source indicator*. Not covered by the OPP CC BY licence.

Figure 5.3 Water abstraction by economic sector in the Netherlands (2000–2022)



Note. Annual total water abstraction by economic sector as defined in NACE (Statistical Classification of Economic Activities in the European Communities) i.e. agriculture (NACE A), mining and quarrying (NACE B), manufacturing (NACE C), electricity cooling (NACE D CL), public water supply (NACE E 36, group NACE G-U) and construction (NACE F) in the Eionet Member Countries, 2000-2022. Hydropower is excluded.
Source. UN SDG 6 Data Portal (2024), *Water abstraction by economic sector - Netherlands*. Underlying data: European Environment Agency (EEA). Not covered by the OPP CC BY licence.

Figure 5.4 Proportion of bodies of water with good ambient water quality in the Netherlands (2023) compared to other countries (SDG indicator 6.3.2)



Source. UN SDG 6 Data Portal (2025), SDG Indicator 6.3.2 – *Water Quality (Netherlands and regional comparison)*. Data provider: UNEP. Not covered by the OPP CC BY licence.

In 2024, drinking water companies supplied 1,094 billion litres of water to Dutch citizens and businesses[351]. In 2019, the Dutch government set a goal to reduce household consumption to 100 litres/day per person by 2035, and business consumption by 20% relative to the reference period of 2016–2019[352]. These goals are not on track to be met. While the goals are clear, implementation of policies and concrete measures are lacking, and consumption is rising. Businesses have been consuming more drinking water in recent years, with particularly high consumption in the food and chemicals sectors[353]. Baseline projections from 2023[354] show that drinking water consumption in the Netherlands will increase from 1,197 billion litres in 2021 to 1,260 billion litres in 2035[355]. Since 2022, dozens of companies have had their applications for a water connection rejected, and many drinking water companies do not have the operational capacity required to deal with unforeseen demand fluctuations[356]. Source water quality (groundwater and surface water) is declining; it contains pharmaceutical residues, agricultural substances, and industrial wastewater which make purification increasingly complex and expensive. Currently 0% of surface water meets EU ecological standards and only 6% meets chemical standards under the Water Framework Directive, which the Netherlands was supposed to meet by 2027[357].

Figure 5.5 Water stress in the Netherlands (SDG indicator 6.4.2)

of the renewable water resources in Netherlands is being withdrawn, after taking into account environmental flow requirements (SDG indicator 6.4.2, 2021)

Source. UN SDG 6 Data Portal (2024), *SDG Indicator 6.4.2 - Water Stress (Netherlands)*. Not covered by the OPP CC BY licence.

To address these challenges, the Dutch government introduced the 2024 Delta Programme, focusing on flood risk management, freshwater availability, and spatial adaptation. Freshwater is one of the three main pillars, with concrete measures aimed at making the Netherlands water-robust and climate-resilient by 2050. The general policy has been set out in the Freshwater Delta Decision, with elements being anchored in the National Water Programme (NWP) and the National Environment Planning Vision (NOVI)[358]. A new priority sequence for regional water management was introduced, which considers spatial planning, economic use of water, water retention, smart allocation, and damage[359]. The three core strategies are: retain water, move water to where it is needed, and reduce freshwater use.

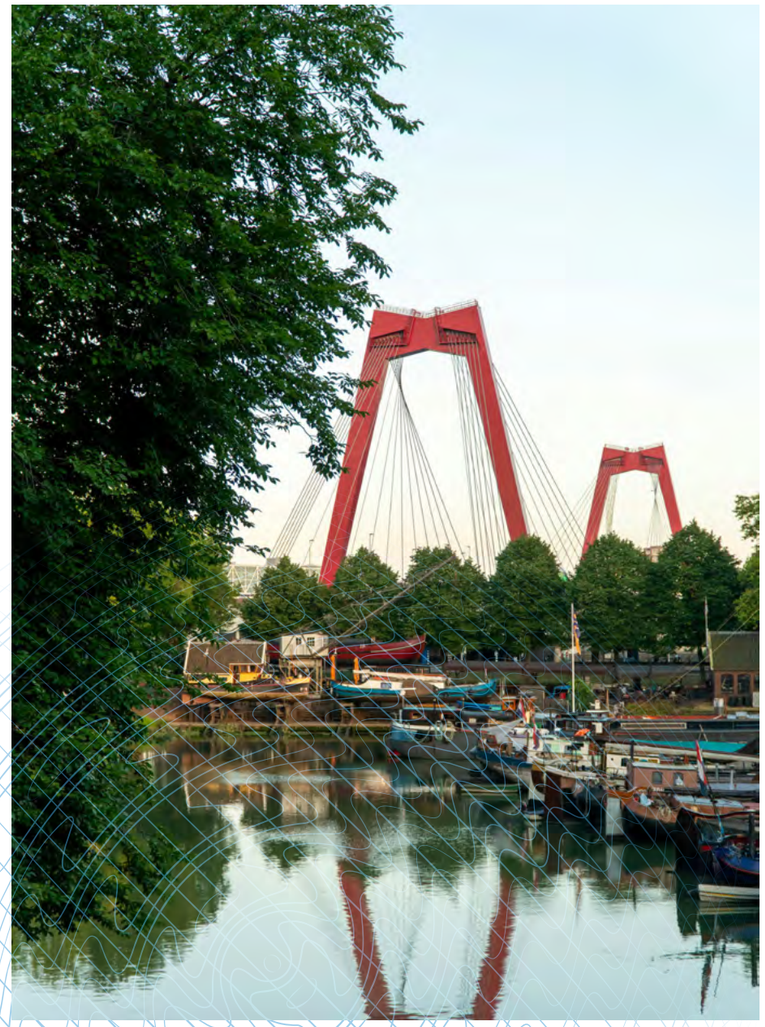
The implementation of this strategy[360] focuses on:

- Collaboration between government authorities and water users
- Making water and soil leading for spatial planning
- Innovation, with over 25 pilot projects on alternative freshwater sources, storage, and intelligent water management
- Financial incentives, including allowances to stimulate measures in freshwater regions (areas in the Netherlands where freshwater supply and management are a top priority)[361]

Context of the Maritime Ecosystem in Rotterdam

Rotterdam's location in the Rhine delta, where Europe's largest river system meets the North Sea, gives the city a unique role at the intersection of freshwater and marine environments. However, reduced freshwater flows increase saltwater intrusion into the delta, harming agricultural areas and degrading groundwater quality[362]. This affects not only Rotterdam but also the wider Rhine-Meuse delta region, which underpins major economic activities and supports millions of people. Port industries in Rotterdam rely heavily on freshwater for operations, cooling, and processing. Climate change and declining river flows threaten these water supplies, and can also disrupt shipping during dry periods when water levels become too low for safe navigation[363].

Rotterdam recently hosted the inaugural **Swimmable Cities Summit**, part of the UN Decade on Ecosystem Restoration (2021–2030). Initiatives like this are crucial for raising public awareness about water quality and highlighting how clean, healthy water systems are central to urban liveability and climate resilience[364].



Direct Impacts of Shipping and Ports: Drivers and Consequences

Oil spills: In 2023, approximately 600,000 gallons (2000 metric tons) of oil were accidentally spilled into marine and freshwater environments worldwide[365] – that's enough to fill about 38,000 standard household bathtubs with a capacity of ~15.7 gallons. However, the largest source of oil pollution in the ocean is not from spills at sea but from land-based runoff, which has been estimated to be 20 times higher than reported two decades ago[366]. Today, it is estimated that land runoff contributes over 1.2 million metric tons (about 360 million gallons)[367] of oil to the ocean every year (equivalent to 23 million standard bathtubs). This oil is washed from roads, cities, vehicles, and industrial sites into rivers and eventually flows into the sea through rain or snowmelt. Land-based runoff is therefore about 605 times larger than accidental spills. Quantifying exact amounts and the contribution of specific activities remains difficult due to a lack of data, from limited monitoring and fragmented reporting. Nonetheless, the scale of land-based runoff highlights the need to tackle oil pollution both on land and at sea to protect freshwater and marine ecosystems.

600,000
gallons/yr of oil spilled into marine and freshwater environments

Sewage: The discharge of raw sewage into rivers and oceans poses serious health risks for people and harms aquatic ecosystems. Sewage depletes oxygen levels in the water suffocating fish and other marine life, and causes visible pollution that can turn coastal areas into unsafe, unpleasant, environments for humans and wildlife[368].

Large vessels, such as cruise ships, can be major contributors to this problem. Globally, the cruise industry alone is estimated to discharge over 1 billion gallons[369] of sewage (over 63 million bathtubs) into the ocean every year. Much of this may only be partially treated or entirely untreated, depending on regional regulations and enforcement. Effectiveness of advanced sewage treatment systems is unclear[370]. This further intensifies pollution in popular coastal destinations and sensitive marine areas.

>1 billion
gallons of cruise industry sewage discharged into the ocean each year

Dredging: Dredging to maintain or increase the depth of navigation channels, anchorages, or berthing areas disturbs river and sea floors and key sedimentary systems, undermining critical delta infrastructure and habitats. Dredging can dramatically alter hydrology (flow velocities, sediment transport), as well as many physical and chemical properties of a water body (pH, dissolved oxygen, redox potential, transparency, temperature)[371]. These shifts can disrupt ecosystems, harm aquatic life and release trapped pollutants. Importantly, in deltas such as the Rhine-Meuse-Scheldt, a *negative sediment budget* now prevails: the amount of sediment removed by dredging and deepening is greater than the sediment being supplied by rivers and the sea. This loss erodes the natural support for shorelines, flood-defences, wetland building and habitat resilience. The pressure is growing as waterways are deepened to accommodate ever larger vessels, and sediment removed for shipping access may ultimately erode the delta's capacity to cope with sea level rise and freshwater intrusion[372].

On the other hand, *environmental dredging*, i.e., targeted removal of contaminated sediments, plays a vital role in ecosystem and human-health protection in urban and industrial zones, where heavy metals and legacy chemicals and other harmful substances are often concentrated[373]. To counter the negative budget, strategies such as sediment reuse for flood protection and sediment traps are being explored[374].

Problem if Not Addressed

Continued pressure on the freshwater boundary poses risks that extend far beyond local water scarcity. It threatens the stability of critical Earth systems and endangers the well-being of both natural ecosystems and human societies.

Ecosystem destabilisation and biodiversity loss: Disrupted freshwater cycles alter regional rainfall patterns, reduce soil moisture, and shift groundwater availability. These changes undermine the viability of forests, wetlands, and grasslands, ecosystems that regulate the climate, purify air and water, and support a vast array of species. As vegetation dies back and habitats degrade, entire food webs can fragment or collapse, pushing species towards extinction and reducing the resilience of ecosystems to other stressors. Over time, these shifts can reinforce global climate feedback loops, such as reduced carbon uptake by drought-stressed forests or expanded desertification, worsening climate change.

Food insecurity and agricultural collapse: Rain-fed agriculture, responsible for over 60% of global cereal production[375], is especially vulnerable to erratic precipitation and prolonged droughts. Crop failures and livestock losses due to insufficient water or extreme weather events can cause food prices to spike, reduce nutritional availability, and increase the likelihood of famines or social unrest in vulnerable regions.

Economic disruption from altered freshwater flows: Changing river flows and shrinking snowpacks reduce freshwater input into estuaries and coastal zones. Both saltwater intrusion from low flows and flooding from high water levels can disrupt these systems, affecting water levels in rivers, damaging crops, degrading drinking water sources, and increasing infrastructure corrosion. All these impacts pose major risks to economic activities such as maritime trade, agriculture, and urban development[376, 377].

In ports and navigable rivers, both low and high water extremes disrupt shipping schedules, raise freight costs, and complicate supply chains. For example, lower water levels have affected European inland shipping considerably in recent years, sending up freight rates, introducing low water surcharges[378], increasing logistics complexity[379] and potentially also affecting vessel resale values. The Rhine and Danube have experienced repeated low water events in recent years, forcing cargo ships to run below capacity or halt operations entirely.

Freshwater security for ports: Reduced water availability impairs the functioning of critical infrastructure, particularly in industrial and port regions. Cooling systems, wastewater treatment, and pollutant dilution all rely on consistent freshwater inputs. Scarcity leads to higher treatment costs, greater pollutant concentrations, and increased health risks for nearby populations. In ports, this also affects operations and regulatory compliance, with potential knock-on effects for trade and urban economies.

Solutions and Maritime Interventions

To address escalating freshwater stress, a range of technological and nature-based solutions are being developed and deployed globally. These interventions aim to decouple water availability from geographic or climatic constraints, improve water-use efficiency, and restore natural hydrological cycles. Below is an overview of leading approaches and how they perform in terms of cost-effectiveness, circularity, and material-energy efficiency.

Nature-Based Solutions (NbS) such as managed aquifer recharge*, wetland restoration†, green roofs, rain gardens, rainwater harvesting, and permeable pavements offer low-energy, low-material interventions that work with natural systems to restore water cycles. By enhancing natural water retention and infiltration, these solutions reduce runoff and flooding, enhance drought resilience, recharge groundwater, improve water quality through filtration, and create co-benefits like urban cooling and biodiversity enhancement. Their material-energy balance is favourable as they rely on natural processes rather than heavy infrastructure. They can also be highly cost-effective over the long term, especially when accounting for avoided flood damage, lower energy use, and public health gains. From a circularity perspective, NbS tend to be strong performers, effectively closing local water loops by mimicking and reinforcing natural hydrological functions.

Desalination technologies, including advanced reverse osmosis systems and newer solar-powered designs, provide freshwater independent of rainfall or river flow, which is especially valuable in arid coastal regions. While traditionally energy-intensive, innovations such as MIT's solar desalination units are beginning to improve the energy profile of this technology, with some experimental systems claiming the potential to produce freshwater at a showing potential to produce freshwater at costs competitive with or lower than municipal tap water[380], depending on local energy prices and infrastructure. However, even with these advances, the material-energy balance remains mixed due to brine disposal and infrastructure requirements. Desalination is moderately cost-effective in water-scarce contexts but less so where water reuse or conservation alternatives are viable. Its circularity is weak, as it transforms seawater into freshwater rather than extending the use of existing water sources.

* Managed Aquifer Recharge (MAR) is a technique where water is intentionally recharged into aquifers for later recovery or environmental benefits. MAR involves various methods, including spreading water on the ground (in infiltration basins or ponds), injecting water into wells, or using in-channel modifications to encourage infiltration.

† Watershed restoration focuses on reducing pollution from various sources, such as runoff, erosion, and industrial discharge.

Water recycling and reuse systems, as exemplified by Israel and Singapore, represent some of the most effective and circular approaches to freshwater sustainability. Israel recycles approximately 90% of its wastewater, with 85% of that used for agricultural irrigation since the 1970s[381], making it a global leader in circular water use. Singapore's NEWater[382] program employs advanced treatment technologies including microfiltration, reverse osmosis, and UV radiation to reclaim water for both industrial and potable use. Singapore supplies up to 40% of its water demand through recycled water[383]. These systems extend the lifecycle of water, reduce dependence on external sources, and enhance national water security. Their material-energy balance is strong, especially when energy-efficient membranes and gravity-assisted flows are used, and their cost-effectiveness is high due to reduced pressure on freshwater ecosystems and lower long-term operational risks. As closed-loop systems, they are exemplary in terms of circularity.

Smart water management leverages digital technologies such as AI, internet-of-things (IoT) sensors, and real-time monitoring tools to detect leaks, optimise water distribution, and enhance overall efficiency. These systems can reduce water loss by up to 25% and lower operational costs[384], making them particularly attractive in urban settings with aging infrastructure. Though the deployment of sensors and digital infrastructure involves some material inputs, the operational material-energy balance is high due to the significant resource savings they enable. Smart systems are cost-effective, offering short payback periods, and their circularity is moderate – they do not close water loops themselves but support conservation and system resilience by preventing unnecessary losses.

Innovative filtration technologies, including nanotechnology-based membranes, graphene filters, and sustainable biofiltration systems, provide advanced contaminant removal at lower energy levels than traditional filtration methods[385]. These technologies enable decentralised water purification and make wastewater reuse more feasible, particularly in rural or remote areas. While some filtration media (e.g., nanomaterials) have higher embodied energy and require careful disposal, the overall material-energy profile is improving with design advancements[386]. Cost-effectiveness is currently variable as some systems are still expensive, but is expected to improve with wider adoption. In terms of circularity, advanced filtration supports water reuse and safe discharge, though end-of-life filter management remains a limiting factor.

Current Contributions and Facts from the Port of Rotterdam

Industrial water use: The Port of Rotterdam is home to a dense cluster of freshwater-intensive industries, including chemical plants, oil refineries, and food processing facilities (cooling). These industries place considerable pressure on both local water demand and potential contamination risks. Much of this demand is met by the Bernisse-Brielse Meer (BBM), a critical freshwater reservoir for the port industry. However, BBM has limited buffer capacity under current usage levels and already experiences shortages during periods of low river flows[387]. This situation is expected to deteriorate further due to climate change, which is reducing average Rhine river flows and increasing the frequency of drought. In parallel, rising sea levels and reduced freshwater outflow are causing greater saltwater intrusion from the North Sea, further compromising the quality of available freshwater[388].

These local constraints reflect a broader national concern: the RIVM projects potential drinking water shortages in all Dutch regions by 2030[389] if no corrective measures are taken. Rotterdam's freshwater resilience therefore cannot be secured in isolation from national water security efforts.

Logistics impact: Low river water levels also disrupt inland shipping, a major logistical artery for the port. The port works with Rijkswaterstaat and inland waterway organizations to address low water level challenges through improved forecasting and alternative transport scenarios, e.g., road and rail[390]. These adaptive logistics strategies are becoming increasingly necessary as extreme low-flow periods become more common due to climate change.

Research and innovation: SmartPort has partnered with Deltalinqs to work with harbour industry to prepare for Water Framework Directive (WFD) requirements.

A self-assessment tool for companies to inventory WFD risks is also being developed. SmartPort has identified the need for joint research on the effects of saltier water on industrial processes, pipelines, and firefighting water reserves. Port of Rotterdam is also looking into developing innovations that address multiple challenges like water quality, availability and safety simultaneously[391]. The Port of Rotterdam has implemented a comprehensive monitoring system, including an Internet of Things platform, to track water and sediment quality. This system uses sensors, AI, and satellite measurements to monitor various aspects of the port, including infrastructure, water, and weather conditions, and provides real-time information for improved decision-making and service delivery[392]. While these measures improve the port's adaptive capacity, they do not address the root drivers of the crisis, particularly the water-intensive and extractive port activities that continue to reinforce and accelerate the very conditions they aim to adapt to.

Recommendations for the Port of Rotterdam

- **Develop solutions to improve stormwater and runoff quality:**
  Develop solutions to treat water runoff and stormwater in port areas in order to enhance water quality. For example, the Port of Avilés in Spain has designed a stormwater system to treat all rainwater and utilise a portion of it. With separation devices and conductors to cisterns allowing the use of recycled water for irrigation, the stormwater system ensures compatibility with non-drinking water quality within the terminal's perimeter[393].

- **Develop binding water efficiency and quality standards:**
  Develop binding water efficiency, re-use and water quality standards for port tenants and shipping companies, with financial incentives for circular water practices and penalties for excessive consumption.

- **Invest in shared water recycling infrastructure:**
  Support shared water recycling infrastructure and treatment facilities that enable industrial symbiosis, allowing compatible industrial processes to reuse treated wastewater from other port operations.

- **Position Rotterdam as a global centre for freshwater–maritime innovation:**
  Strengthen Rotterdam's role in freshwater–maritime innovation by scaling up research into innovative solutions that address water quality, availability and safety challenges simultaneously.

- **Require transparent water accounting across the port area:**
  Mandate transparent water accounting by requiring all companies operating in the port area, as well as the port authority, to publicly report their annual water use, reuse, and discharge volumes.

- **Use non-potable water for industrial purposes:**
  Use water that is not safe for drinking for industrial activities instead of using high-quality drinking water.

Recommendations for Policymakers

- **External water footprint strategy:**
  Address the Netherlands' 4,000 liters/day per capita water footprint (most of it embedded in imported products) by exploring trade policies that account for virtual water (i.e., the freshwater used abroad to produce goods consumed in the Netherlands) imports and support water-stressed exporting countries, e.g., incentivising suppliers to adopt water-efficient practices, requiring water footprint disclosures in supply chains, and reducing dependence on imports from regions facing severe water scarcity.

Global issue

Address the Netherlands' external water footprint by tackling embedded water in imports through trade policy, supply-chain transparency, and support for water-stressed exporting regions.

- **Accelerate Delta Programme implementation:**
  Close the gap between the 2050 water resilience targets and current on-the-ground progress by establishing binding interim milestones, supported by legal enforcement mechanisms for the "water-led spatial planning" approach, ensuring that land use and infrastructure decisions are aligned with future water availability. Explore collaborations with Germany and upstream Rhine countries on transboundary river management.

- **Enforce consumption targets:**
  Implement mandatory measures to achieve the 100 liters/day per person by 2035 target, moving beyond voluntary guidelines to include mandatory water quotas for high-consumption sectors and connection restrictions for non-compliant businesses.

- **Address data gaps and reporting:**
  Harmonise datasets and methodologies to enable consistent water accounting and policy benchmarking. A critical gap remains in the lack of regionally specific planetary boundary assessments for freshwater.

- **Integrate soil health into water policy:**
  Healthy soils play a key role in water retention and drought resilience. Incorporating soil quality restoration targets, such as increasing organic matter content, into national and regional water strategies can enhance natural water storage, reduce runoff, and improve ecosystem functioning.

Conclusion and Call to Action

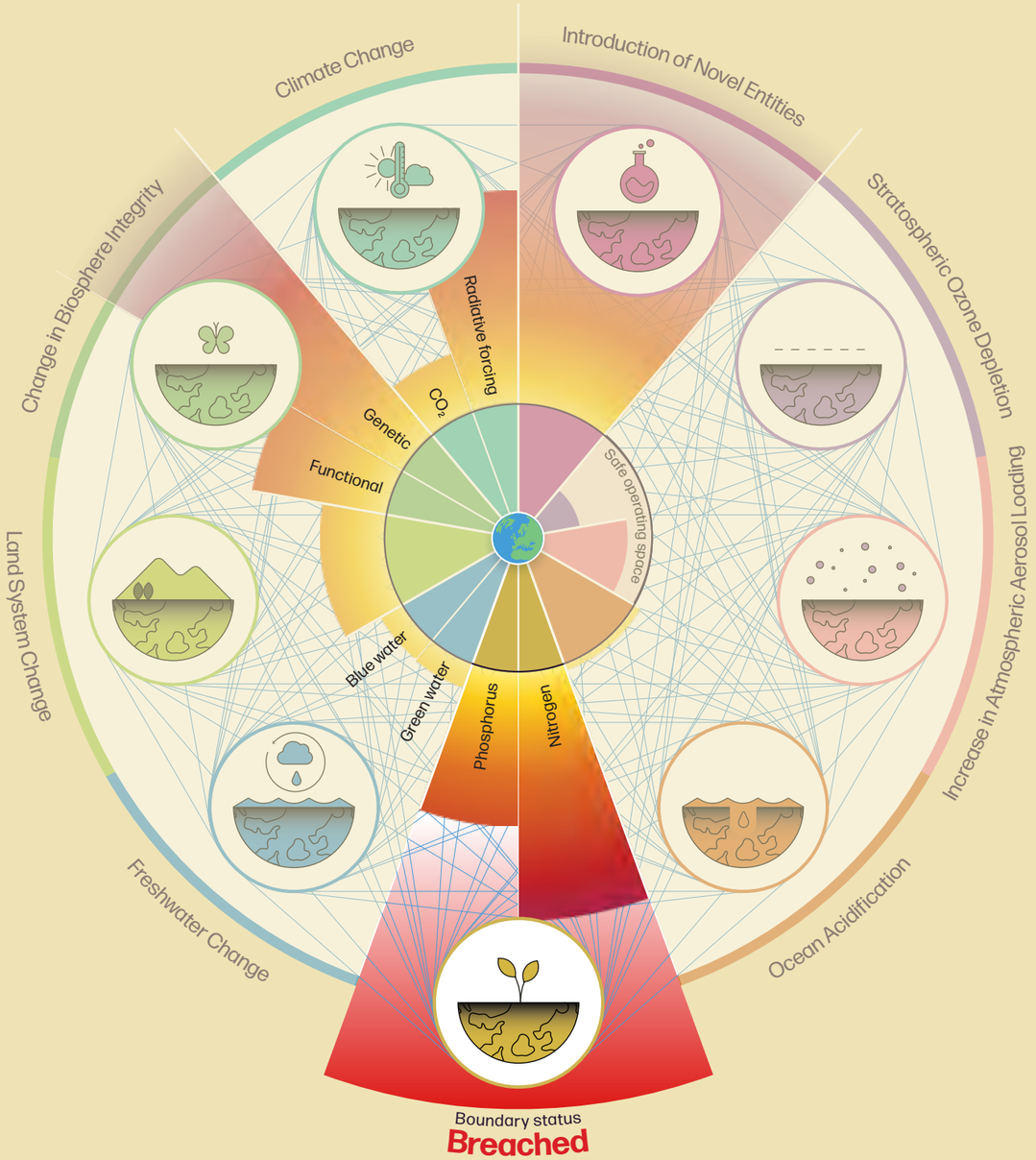
The RIVM's 2024 assessment warns that, without swift action, the Netherlands could face nationwide drinking water shortages by 2030, a timeline that leaves little margin for delay. This underscores that addressing freshwater boundary transgression is no longer a distant environmental goal but an immediate national priority[394].

Addressing the transgression of the freshwater planetary boundary requires more than technological solutions like desalination or smart water management. It demands a fundamental shift towards water-led spatial planning and circular water systems that treat freshwater not as an unlimited input for economic growth, but as a finite and life-sustaining planetary resource. The Netherlands possesses the knowledge, infrastructure, and innovation capacity to lead this transformation, yet leadership will depend on accelerating implementation, enforcing binding consumption targets, and embedding planetary boundary thinking into all water-related decisions, from local land use to national policy.

This transformation also demands that the port's operations become fully aligned with ecological limits, not by facilitating activities that drive climate and freshwater crises, only to implement measures that soften their impacts, but by fundamentally shifting towards enabling activities that, on balance, do no harm. True leadership means no longer managing the consequences of harm while continuing to cause it.

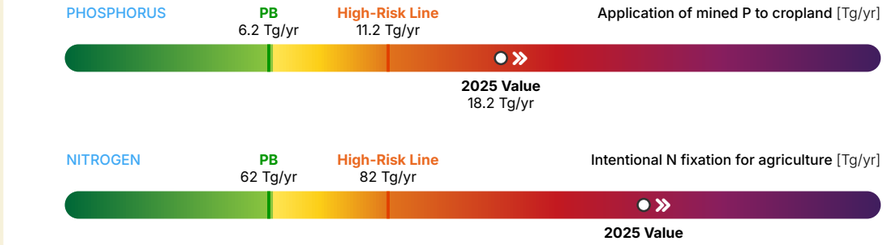
"Do unto those downstream as you would have those upstream do unto you."
Wendell Berry

CH6 Modification of Biogeochemical Flows



CH2 Climate Change
CH3 Change in Biosphere Integrity
CH4 Land System Change
CH5 Freshwater Change
CH6 Modification of Biogeochemical Flows
CH7 Ocean Acidification
CH8 Increase in Atmospheric Aerosol Loading
CH9 Stratospheric Ozone Depletion
CH10 Novel Entities

Figure 6.1 Planetary Health Check 2025 status: Modification of Biogeochemical Flows



Source. *Planetary Healthcheck 2025*. CC BY 4.0.

Introduction to the Boundary (Global)

Nitrogen and phosphorus are essential nutrients needed by animals and plants, to produce important building blocks such as proteins and DNA. In nature, these nutrients move around in balanced cycles between soil, water, air, and living creatures. Human activity has broken these natural cycles by adding far too much nitrogen and phosphorus to the environment through, for example, fertilisers used on farms that wash into rivers and seas, burning of fossil fuels which releases nitrogen compounds into the air, and industrial processes that convert inert atmospheric nitrogen into reactive nitrogen.

We've crossed the safe limits for both nutrients, which is causing serious problems for nature and people.

Agriculture is the primary cause of the disruption to the nitrogen and phosphorus natural cycles, through synthetic fertiliser production and use, intensive livestock farming, and rock phosphate mining[395]. The individual effects of nitrogen and phosphorus multiply when both nutrients occur in excess[396]. Unlike nitrogen, which can be extracted from the atmosphere, phosphorus is mined from increasingly limited and finite rock deposits. Meanwhile, much of the mined phosphorus ends up polluting water systems rather than being recycled back into agricultural use, creating both scarcity and environmental problems.

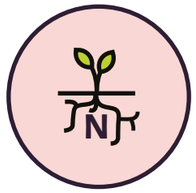
The boundaries were first crossed in 1970 for nitrogen and 1964 for phosphorous[397]. Today, the amount of human-derived nitrogen entering the biosphere annually roughly equals all natural sources combined, meaning humans have doubled the total reactive nitrogen entering ecosystems[398].

The nitrogen boundary indicator, called *industrial and intentional biological fixation of nitrogen (Tg/yr)**, refers to humans converting atmospheric nitrogen gas (N_2) into forms that plants and living organisms can use, called reactive nitrogen (Nr). This process is called "nitrogen fixation." Before modern industrial farming, humans only fixed about 62 million tons of nitrogen per year (62 Tg/yr). Scientists say we should stay below 82 million tons per year as the safe boundary, but the current value is 190 million tons, mainly due to fertiliser use[399].

We are now fixing more than double the safe boundary level, and over three times the natural baseline!

This nitrogen overload pollutes water[400], harms wildlife[401], and worsens climate change[402]. Of the nitrogen used in food production, over 50% supports animal agriculture, but only about 23% of all nitrogen inputs actually ends up consumed as human food – the rest is lost to the environment through various pathways[403].

The phosphorus boundary indicator, called *regional phosphorus flow from fertilizers to erodible soils (Tg/yr)* measures how much phosphorus is added to soils that are at high risk of losing the phosphorus to water systems. This phosphorus is intended to help crops grow but often ends up washing off farmland into rivers, lakes, and coastal areas. Before modern industrial farming, humans only added about 6 million tons of phosphorus to the environment per year. Scientists say we should stay below 11 million tons per year to avoid large-scale water pollution, but today we add around 18 million tons each year[404].



We are now adding far more reactive nitrogen to the environment than nature can safely handle – over twice the safe level and more than three times the natural level.

* Tg/yr = Teragrams / year = Million tons / year

We're about 65% above the safe boundary of phosphorus, and three times the pre-industrial baseline!

This phosphorus overload fuels harmful algal blooms, creates ocean dead zones, and disrupts freshwater and marine ecosystems[405]. Similarly to nitrogen, a large share of phosphorus supports animal feed production, with smaller amounts going to direct human food production, and significant amounts lost as runoff and waste.

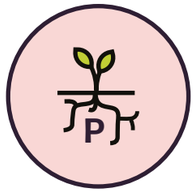
Nutrient pollution poses severe risks across three critical areas if not addressed:

- **Aquatic ecosystem collapse:** Excessive nitrogen and phosphorus cause algae blooms, aNO_xic conditions (areas completely lacking oxygen, suffocating fish and aquatic creatures), and eutrophication (excessive nutrient enrichment that disrupts aquatic ecosystems), leading to dead zones, fish kills, toxin production (that can contaminate seafood and drinking water), altered plant species diversity, food web disruption (for example, the loss of tiny shelled plankton that starves fish and seabirds), tourism disruption, and health issues. Nutrient pollution can also cause acid rain, which damages life on land as well as in water[406].

- **Economic impacts**: According to UNEP's 2018-2019 Frontiers Report, nitrogen costs the global economy between US$340 billion and US$3.4 trillion annually when considering its impact on human health and ecosystems[407]. Fishing and shellfish industries are hurt by algal blooms that kill fish and contaminate shellfish, causing losses in the order of tens of millions of dollars[408]. Polluted waters deter visitors causing tourism losses, properties near water bodies with the unpleasant sight and odour of algal blooms can lose value, and municipalities face increasing costs to treat contaminated drinking water[409].

- **Human health impacts:** Water containing elevated levels of nitrate can deprive infants of oxygen by interfering with their blood's ability to carry it, turning their skin blue and leading to the life-threatening 'blue baby syndrome'; it also increases the risk of cancer in adults[410]. Polluted water can cause gastrointestinal illness and infections if people swim in it or drink it.

One major example of disrupted nitrogen flows is the release of ammonia into the atmosphere from livestock housing, manure storage and application, and synthetic fertiliser use. Once airborne, ammonia reacts with atmospheric acids to form ammonium nitrate and ammonium sulfate, which are major components of fine particulate matter ($PM_{2.5}$); these fine particles reduce air quality and pose serious health risks[411]. Additionally, nitrogen from fertilisers and manure undergoes microbial transformations in soils that produce nitrous oxide, a potent greenhouse gas. These interconnected effects illustrate how exceeding the nitrogen boundary not only destabilises ecosystems but also directly harms human health and contributes to climate change.



We are adding about 65% more phosphorus to the environment than the safe boundary allows , and three times the pre-industrial baseline!

This planetary boundary is deeply interconnected with other boundaries:

Land System Change: Agriculture drives habitat conversion (turning natural areas into farmland, destroying habitats and threatening wildlife) and is identified as a threat to 24,000 of the 28,000 (86%) species at risk of extinction in 2021[412].

Climate Change: Growing of crops and livestock for food, and raw materials for non-food consumption account for 14% of global GHG emissions over 2015–2024[413]. Nitrous oxide (N_2O) from fertilisers is a potent greenhouse gas[414] that has a global warming potential 273 times higher than CO_2. Beyond agricultural emissions, energy systems are also major contributors to nitrogen-related emissions. Both fossil and renewable fuels can produce nitrogen oxides (NO_x) when combusted. Compared to fossil diesel, high quality biodiesels may produce higher NO_x emissions when used in diesel engines[415] depending on engine loads[416], even if they help reduce other emissions like particulates[417]. Ammonia combustion (due to ammonia-air mixtures and ammonia slip)[418, 419] and methanol combustion also produce NO_x emissions, though levels may be different from fossil fuels[420].

Biosphere integrity: Nutrient pollution creates dead zones that eliminate marine life, causes eutrophication (the excessive growth of algae and plants caused by nutrient overload) and disrupts and harms ecosystem composition in both land and water[421]. Nitrogen pollution is the most prominent driver of human-made biodiversity decline after habitat destruction and the emission of greenhouse gases[422].

Freshwater Change: Food production for livestock and humans generates huge freshwater demand[423], nutrient runoff pollutes freshwater systems[424], and unsustainable agricultural practices alter natural water cycles[425].

National Context: The Netherlands

The groundwater and surface water in the Netherlands do not meet the targets of the European Nitrates Directive as they contain too much nitrogen and phosphorus. There has been no clear water quality improvement since 2012. Nitrate concentrations in groundwater under farms increased from 2016–2019, and from 2020–2023. About 44% of lakes, rivers, and canals in the Netherlands do not support a healthy and diverse aquatic ecosystem, because the water is too polluted to sustain enough species. Only 11% of these water bodies still support a sufficient diversity of plant and animal species, despite nitrogen and phosphorus concentrations remaining too high. In addition, problems already occur, or are expected to arise soon, at around 20% of groundwater extraction points[426].

The European Commission's zero pollution action plan (ZPAP) aims to reduce pollution in the EU to levels not harmful to human health or ecosystems. Target 3 of the plan sets a clear objective to reduce the area of ecosystems where nitrogen deposition exceeds critical loads by 25% by the year 2030, compared to levels in 2005[427]. Between 2005 and 2022, the Netherlands reduced the area of nitrogen-sensitive nature exceeding critical loads by approximately 9% (from 80% to 71% of Natura 2000 areas), well below the EU-wide average progress of 13%[428]. Looking at all Dutch terrestrial ecosystems, the percentage with low environmental quality in terms of nitrogen deposition decreased from 64% in 1994 to 25% in 2022, but improvement stalled between 2010 and 2018, primarily because ammonia emissions hardly decreased during this period. Only 4% of terrestrial ecosystems achieved high environmental quality as of 2022. Ammonia emissions are responsible for about two-thirds of all nitrogen deposition in the Netherlands, and most of this ammonia is agricultural in origin. At the current pace and without stronger policies or additional measures, the Netherlands is not on track to meet the ZPAP target by 2030.

When looking at all the nitrogen that is deposited (falls from the air onto land) in Natura 2000 areas in the Netherlands, about 60% of it originates from sources inside the Netherlands ("national contribution"). Of this, around 20% comes from traffic, industry and consumers. The other 40% comes from livestock farming[429]. To arrive at substantial cuts in emissions, both livestock farming and transport will need to be changed.

The Netherlands has been experiencing a severe nitrogen crisis since 2019, when the Council of State ruled that the government's nitrogen management system was invalid, suspending an estimated 18,000 construction projects worth ~ 14 billion EUR[430]. Construction of new highways, housing blocks, airports, wind farms and a range of other crucial infrastructure also suffered delays due to this[431].

In response to a case by Greenpeace[432], against the Dutch government for not doing enough to lower high levels of nitrogen oxide emissions caused by intensive farming and heavy use of fertilisers, as well as traffic and construction in the country, a court in the Hague ordered the government to meet its target of reducing the emissions to legally allowed levels in 50% of all affected nature reserves by 2030. The court also set a fine of 10 million EUR if the goal was not met, a sum unlikely on its own to provide a major impetus for change. Out of all the nature reserves that are affected (protected Natura 2000 areas), the Netherlands has succeeded in bringing nitrogen emissions down to legally allowed levels in 28% of them so far[433].

Between 2015 and 2023, maritime NO_x emissions increased by 10% across the EU, with especially sharp rises of 33% in the Atlantic and 32% in the Arctic regions.

Direct Impacts of Shipping and Ports: Drivers and Consequences

Although maritime contributions of nitrogen and phosphorus are smaller than those from agriculture, they can still cause significant local impacts. Ships and port activities can introduce nutrients directly into sensitive marine ecosystems or concentrate them in ecologically important coastal zones. Furthermore, port cities are often located at river mouths, where agricultural runoff and other terrestrial nutrient sources converge with effluents from shipping and port operations, increasing the overall nutrient load in these vulnerable areas.

Atmospheric (NO_x and N_2O) emissions from ships: Ship engines emit nitrogen oxides (NO_x) that ultimately get deposited into marine and land ecosystems as reactive nitrogen (Nr). Maritime NO_x emissions are regulated under IMO MARPOL Annex VI with three tiers of increasingly strict standards, but compliance challenges persist. This is due to insufficient monitoring and enforcement, as well as the fact that stricter NO_x limits apply only to new ships, many older vessels continuing to emit higher levels legally, and some ships not properly using or maintaining emission reduction technologies. Between 2015 and 2023, maritime NO_x emissions increased by 10% across the EU, with especially sharp rises of 33% in the Atlantic and 32% in the Arctic regions. This trend occurred despite the designation of the North Sea and Baltic Sea as NO_x Emission Control Areas (NECAs) since 2021[434], where stricter emission standards apply to new ships. However, these requirements do not affect older vessels, which are still allowed to operate with higher emission levels[435], contributing to ongoing overall increases.

Research by the International Council on Clean Transportation found that, in practice, Tier II engines often show higher NO_x emission rates than expected when operated at low loads, and in some cases similar or even higher real-world emissions than older Tier I or unregulated Tier 0 engines. This suggests that current regulations (Tier II) are not effectively reducing emissions. The study also revealed that ships typically operate at lower engine loads than assumed in current NO_x test cycles, with the highest emission rates occurring at main engine loads below 25%, averaging 12 g/kWh compared to 8.1 g/kWh at loads greater than 75%[436]. Although newer ship engines are supposed to emit less NO_x, in reality they often emit as much or more than older engines because they operate at low power most of the time, where emissions are actually higher – a situation not well covered by current test procedures.

While NO_x emissions from marine engines have received significant regulatory attention[437], nitrous oxide (N_2O) emissions remain incompletely monitored[438] and regulated, despite their high global warming potential, approximately 273 times that of CO_2 over a 100-year timescale[439]. Although N_2O can be measured during engine operation, comprehensive international protocols for monitoring across all engine types are missing. As a result, many engine manufacturers do not incorporate N_2O assessments into standard testing and reporting practices. This incomplete regulatory framework risks underestimating the climate impacts of maritime combustion, particularly as N_2O formation is influenced by variables such as fuel composition, engine load, and combustion conditions[440].

Sewage discharges: Ships discharge sewage containing nitrogen and phosphorus directly into marine waters (allowed in the open sea, beyond 12 nautical miles from the nearest land)[441], which can create health hazards and contribute to oxygen depletion and eutrophication in coastal areas. MARPOL Annex IV prohibits sewage discharge within specified distances from land unless ships have approved sewage treatment plants, with passenger ships in special areas required to meet enhanced nitrogen and phosphorus removal standards[442]. Many treatment systems don't fully remove nutrients before discharge into marine waters[443]. Although most countries have strict rules to prevent sewage discharge, many coastal areas lack proper laws and enforcement mechanisms[444]. Even if waste is dumped far offshore, it does not remain isolated; it circulates globally and ultimately returns to impact coastal ecosystems and human health. Additionally, port-adjacent and fence-line communities, including workers and nearby residents, face disproportionate exposure to air pollution[445].

In addition to sewage discharge, nitrogen pollution can also result from tank cleaning operations (degassing) when vessels carrying fertilisers or nitrogen-based chemicals purge or wash their tanks. These washings can release highly concentrated nitrogen residues directly into port waters if not properly treated or managed[446], contributing to local nutrient spikes and air emissions.

A related concern is *floating degassing*, i.e., the release of gaseous residues during tank cleaning while vessels are at anchor or underway. International maritime law explicitly allows states to regulate such emissions domestically, and despite Dutch government's claims to the contrary, the international legal framework recognises sovereign rights to enact national legislation concerning degassing to protect public health and the environment, and may even create obligations to do so under human rights law[447].

Stormwater runoff: Port areas collect nutrient-rich runoff from surrounding industrial, urban, and cargo-handling activities. Storm drainage systems can channel this contaminated water directly into marine environments and deliver concentrated nutrient loads to sensitive coastal ecosystems[448]. This leads to algal blooms, oxygen depletion (dead zones), and overall deterioration of water quality and marine biodiversity.

Industrial activities in the port: Ports may host fertiliser handling and storage, chemical processing, and agricultural product handling facilities that can contribute to nutrient pollution through spillage, dust[449], and industrial discharge (any liquid, or sometimes gas waste released from industrial facilities).

Solutions and Maritime Interventions

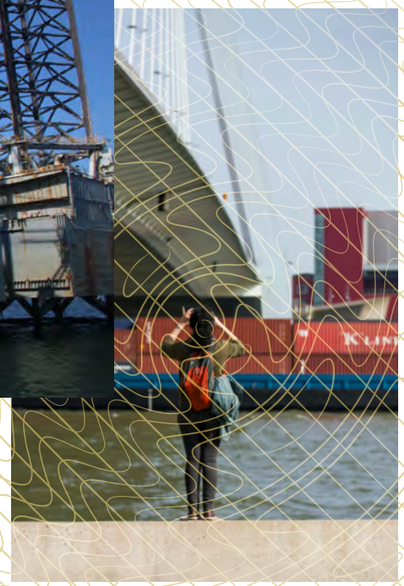
While agricultural and general land-based solutions address most nutrient sources, ports contribute both land-based and maritime-derived nutrient emissions, making maritime-specific approaches to nutrient reduction essential for ports and coastal areas.

Agricultural innovations: Regenerative agricultural practices aim to restore soil health, improve biodiversity, and rebuild natural nutrient cycles[450] rather than merely sustaining existing systems. Approaches such as using cover crops (planted to enrich soil and capture residual nutrients), crop rotation, planting vegetation along field edges to absorb nutrients before they reach waterways[451], and simply applying less fertiliser can all significantly reduce nutrient runoff from agricultural lands. Additionally, regenerative systems often incorporate reduced tillage to improve soil structure and water retention, and integration of livestock to enhance nutrient cycling. Precision agriculture, using sensors and GPS to apply fertilisers and manure, only where and when needed, can further complement these nature-based solutions.

Enhanced enforcement of regulations: Stronger enforcement of existing regulations can substantially reduce nutrient pollution. Although the EU Nitrates Directive[452] sets a strict limit of 50 mg/L of nitrate in groundwater and drinking water sources, enforcement gaps remain.The EU has initiated infringement proceedings against multiple member states for violations, yet full compliance appears to be distant[453]. Several countries (Belgium, Denmark, Ireland, Italy and the Netherlands) received repeated exemptions (derogations), allowing higher nutrient applications than regulations specify[454], including reasons around high livestock densities, intensive grassland use, or the ability of certain crops and soils to absorb more nitrogen under strict conditions. However, they have contributed to persistent water quality problems which is why the EU has decided to phase out the Dutch derogation completely by 2026[455].

Strengthening enforcement with meaningful financial penalties and closing regulatory exemptions could dramatically improve compliance.

Strengthening relevant policies: The EU's revised Urban Wastewater Treatment Directive entered into force on 1 January 2025[456]. This is meant to strengthen nutrient pollution control by requiring tertiary treatment (removes nutrients which are not fully removed in primary and secondary treatment) for nitrogen and phosphorus removal at all large wastewater treatment plants (150,000+ population equivalent) by 2039 and extending these requirements to medium-sized plants (10,000+ population equivalent) by 2045[457]. The revised directive also introduces new requirements to recover valuable components (including phosphorus and nitrogen for fertilizers, organic matter for biogas, and even reclaimed water) from wastewater and sewage sludge, promoting circular economy approaches rather than simply treating nutrients as waste[458]. This represents a major shift from the previous directive, which only required basic treatment, and will help tackle eutrophication in sensitive water bodies like the Baltic and North Sea.



Shift towards plant-forward diets: Shifting towards more plant-based diets (or at very least away from beef) reduces nutrient pollution by decreasing demand for resource-intensive livestock farming[459]. Animal agriculture requires substantially more nitrogen and phosphorus per calorie produced than plant crops[460]. Additionally, beef requires 20 times more land and emits 20 times more emissions per gram of edible protein than common plant proteins such as beans[461]. Plant proteins like legumes naturally fix nitrogen (even up to 50–80%[462*]) from the atmosphere and can add nitrogen to soil for use by subsequent crops, reducing total nitrogen fertiliser needs[463].

Phosphorus recovery, efficiency and recycling: Techniques such as using specialised bacteria to capture phosphorus from wastewater[464], adding chemicals (like alum or iron salts) to bind and remove it, and converting nutrients from manure and wastewater into organic fertilisers for reuse in agriculture can all significantly reduce phosphorus pollution[465] and close nutrient loops.

Advanced wastewater treatment technologies (on land and on vessels): New methods like anammox (anaerobic ammonium oxidation)[466] and membrane bioreactors (MBRs)[467] can greatly improve nitrogen removal from wastewater, reducing nutrient pollution before it can reach rivers, seas, and coastal areas.

Upgrading ship sewage treatment systems beyond current MARPOL standards to achieve higher nitrogen and phosphorus removal rates can help reduce the harm of shipping on nutrient flows. Advanced ballast water treatment systems, while primarily designed to prevent transfer of invasive organisms between marine regions, can also reduce some incidental nutrient transfer, though this is a secondary benefit rather than the primary function of these systems.

* The amount of nitrogen fixed varies according to the legume species and variety. Within a species, the amount of nitrogen is directly related to (dry matter) yield. Most grain legumes can obtain between 50 and 80% of their total nitrogen requirements through biological fixation, but some, like faba bean will fix up to 90%. *https://www.saskatchewan.ca/business/agriculture-natural-resources-and-industry/agribusiness-farmers-and-ranchers/crops-and-irrigation/soils-fertility-and-nutrients/soil-improvements-with-legumes*

Enhanced ship emissions controls: Stricter nitrogen oxide (NO_x) emissions standards for shipping, combined with strong port-state control enforcement can greatly reduce nutrient pollution from maritime activities. By cutting NO_x emissions, these measures directly reduce reactive nitrogen deposition into coastal and marine environments, preventing algal blooms and oxygen depletion. Current IMO regulations could be further tightened, while ports can encourage the use of ultra-low NO_x vessels by offering incentives through improved environmental ship indexing systems (which may now be possible due to the availability of advanced sensors and AI technologies).

Stormwater management innovations: Innovative stormwater management solutions such as permeable pavements, green roofs, and bioretention systems (landscaped shallow depressions), can help to capture and treat stormwater runoff, reducing the amount of nutrients entering waterways.

Shore power and transition to clean marine fuels: Shore power expansion will reduce in-port emissions. Shore power allows ships to plug into the local electricity grid instead of running their auxiliary engines which emit NO_x, SO_x, CO_2 and particulate matter, including nitrogen emissions that contribute to nutrient pollution. By cutting NO_x emissions, shore power directly reduces reactive nitrogen deposition into nearby coastal waters, preventing eutrophication, protecting marine life, and improving water quality as well as air quality. The transition to clean marine fuels offers promise but requires careful consideration, as many proposed technologies remain more optimistic visions than practical realities, or aren't yet commercially ready or widely available.

Fuels like hydrogen and ammonia (NH_3) face significant technical, safety, and/or economic challenges before they can be deployed at scale. For example, combustion of both fuels produces nitrogen oxides (NO_x); the quantity of NO_x depends on the combustion temperature and availability of air. NO_x emissions are controllable through optimised combustion design and aftertreatment systems like selective catalytic reduction (SCR). Ammonia fuel also poses risks of NH_3 slip that could contribute to marine nitrogen pollution and even small releases of N_2O (as little as 0.4% of the nitrogen in ammonia fuel emitted as N_2O across the entire value chain, from production to combustion) could cancel out any climate benefits of using NH_3 instead of fossil fuels[468]. It's important to remember that N_2O is a greenhouse gas and contributes to reactive nitrogen pollution and stratospheric ozone depletion. In addition, NO_x and NH_3 can act as indirect GHGs by increasing the atmospheric concentration of N_2O. When emitted to the environment, NH_3 and NO_x can transition through a range of chemical reactions as part of the nitrogen cycle, eventually forming "indirect N_2O"[469, 470]. This can occur both by oxidation of NH_3 in the atmosphere, and by conversion of Nr to N_2O after deposition on soils and waters[471, 472]. These indirect N_2O emissions are not currently accounted for by the IMO's GHG Studies, nor are they addressed by proposals as part of Shipping's Net Zero Framework (see climate chapter).

Marine and coastal ecosystem restoration: Mangroves, seagrasses, tidal flats[473] and seaweed[474] act as natural filters, absorbing excess nutrients from the water and sediment, improving water quality and supporting overall ecosystem health[475, 476].

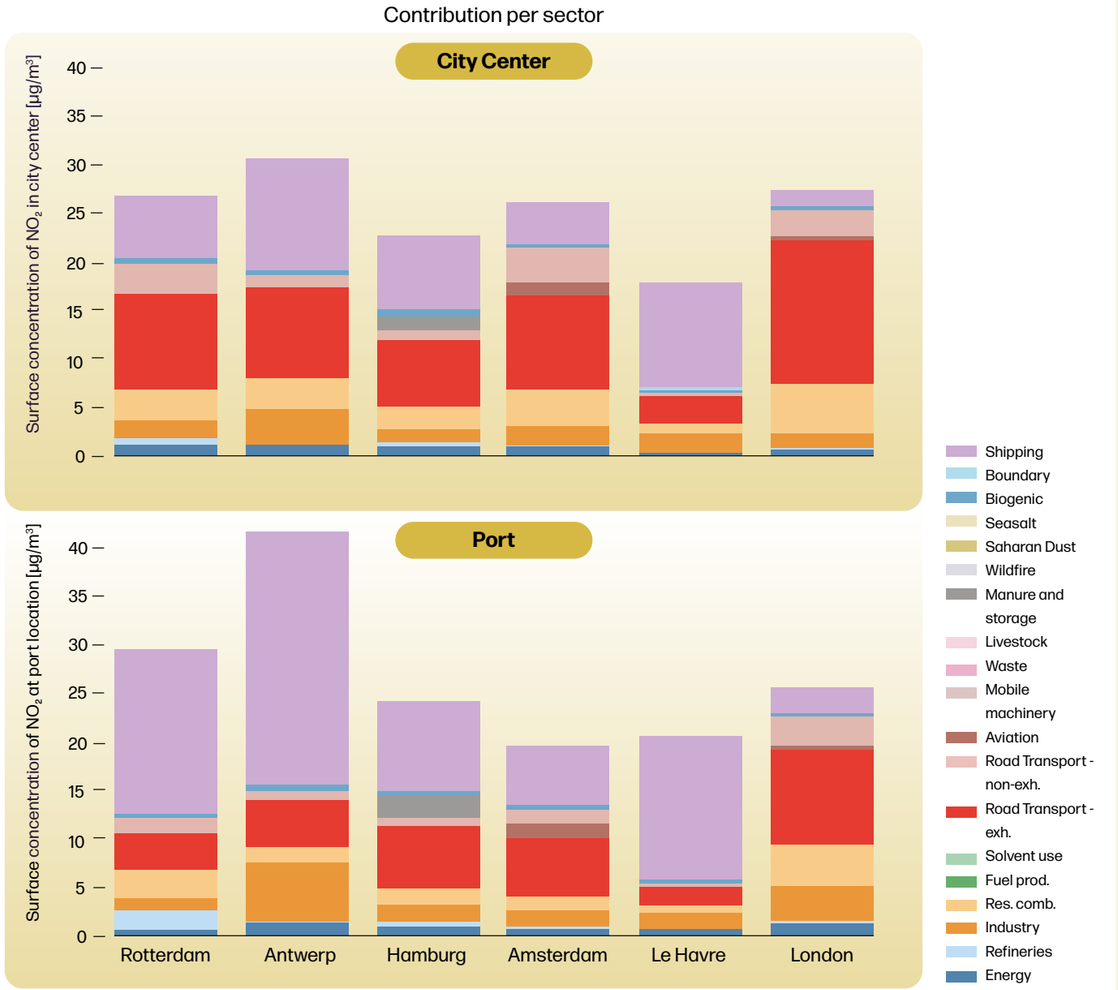
Green Shipping Corridors: Maritime green corridors initiatives[477], which are currently focused on fuels, could be extended to cover waste management and other sources of marine pollution, creating demonstration zones for best practices in marine environmental stewardship.

Port-Based Circular Economy Hubs: Developing ports as nutrient recovery centres, capturing and processing nitrogen and phosphorus from ship waste streams, port operations, and industrial activities for reuse in regional circular economy systems can support ports' transition into future-proof business models.

Current Contributions and Facts from the Port of Rotterdam

Air quality in cities with large maritime ports is seriously harmed by emissions from shipping activities, which now make up a growing share of urban air pollution. In six major European port cities (Rotterdam, Antwerp, Hamburg, Amsterdam, Le Havre, and London) studies show that shipping contributes between 6.5% and 62% (equivalent to 1.8–11.5 µg/m³) of nitrogen dioxide (NO_2) concentrations in city centers[478]. These dangerous levels of NO_2 directly threaten public health, increasing the risk of respiratory diseases, cardiovascular problems, and premature death[479].

Figure 6.2 Source attribution of NO_2 concentrations in European port cities and port areas



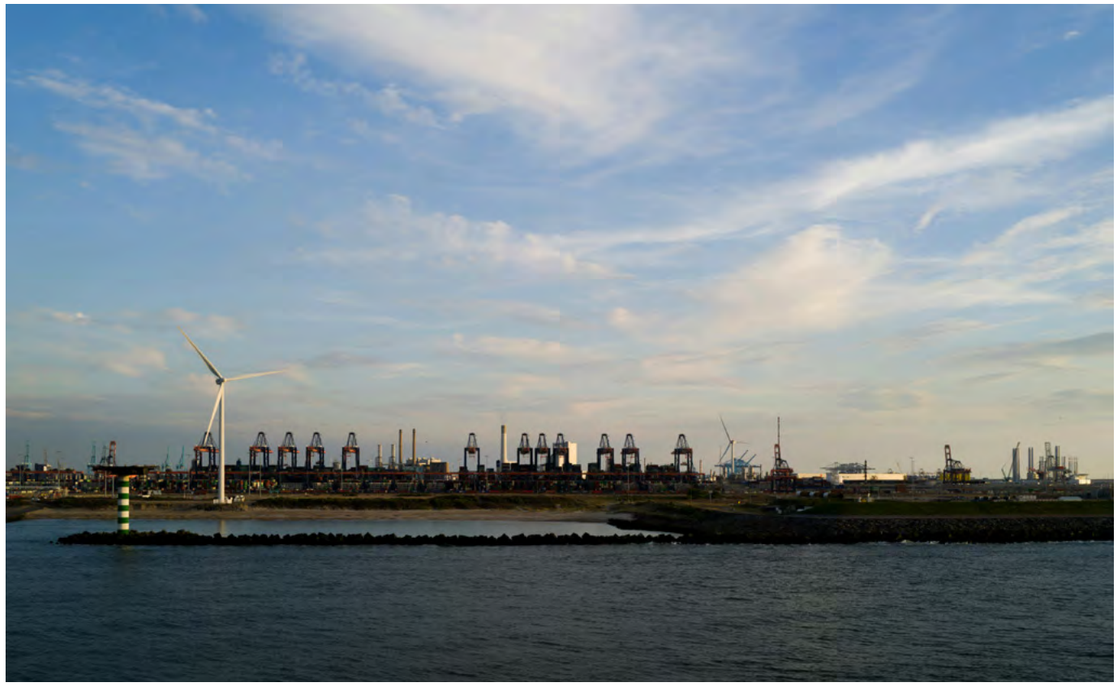
Note. The source attribution results showing the contribution from the various sectors to the annual average NO_2 concentration for the six city centres and the ports. The average contribution from shipping in the chosen city centres is 28%, making this the second largest contributor after road transport exhaust emissions (35%). In the ports, the contribution to the NO2 concentration originating from shipping emissions is higher at 47%.
Source. Tokaya et al. (2024), *The impact of shipping on the air quality in European port cities with a detailed analysis for Rotterdam*, Environmental Pollution Advances. Not covered by the OPP CC BY licence.

Table 6.1 Predicted annual average NO_2 concentrations and major source contributions in six European port cities

Concentration [µg/m³] (%)	Rotterdam	Antwerp	Hamburg	Amsterdam	Le Havre	London	Average
City centre							
Total	26.4	30.2	22.6	25.8	17.5	27.1	24.9
Shipping	6.3 (24%)	11.5 (38%)	7.6 (34%)	4.4 (17%)	10.8 (62%)	1.8 (6.5%)	7.1 (28%)
Road Transport - exhaust	9.5 (36%)	9.1 (30%)	6.8 (30%)	10.0 (39%)	2.8 (16%)	14.4 (53%)	8.7 (35%)
Port							
Total	29.0	41.2	24	19.2	20.2	25.3	26.5
Shipping	16.7 (58%)	26 (63%)	9.3 (39%)	6.0 (31%)	14.6 (72%)	2.8 (11%)	12.6 (47%)
Road Transport - exhaust	3.8 (13%)	4.6 (11%)	6.4 (27%)	5.6 (29%)	1.9 (9.4%)	9.5 (38%)	5.3 (20%)

Note. Predicted annual average NO_2 concentration in the six city centres (top 3 rows) and ports (bottom 3 rows) and the relative contributions of the two most important contributing sectors (i.e., shipping, road transport-exhaust).
Source. Tokaya et al. (2024), *The impact of shipping on the air quality in European port cities with a detailed analysis for Rotterdam*, Environmental Pollution Advances. Not covered by the OPP CC BY licence

In 2024, the Port of Rotterdam reported an annual average nitrogen dioxide (NO_2) concentration of 20.4 µg/m³ in the wider Rotterdam region. This already exceeds the new European limit value of 20 µg/m³ that will come into force on 1 January 2030[480], underscoring the urgent need for action. While the port currently operates under The Living and Working Environment (Quality) Decree (Besluit kwaliteit leefomgeving), it is now working to meet the stricter standards set by the updated European Air Quality Directive[481] to better protect public health.



Recommendations for the Port of Rotterdam

- **Strengthen NO_x and N_2O monitoring and reporting:**
  Move beyond periodic estimates and carefully chosen monitoring sites by developing a comprehensive, real-time sensor network throughout the port. This should include independent placement of sensors at pollution hotspots and community fence-line areas, in addition to background locations, to ensure a true representation of environmental and public health impacts. Install continuous NO_x and N_2O sensors at multiple strategic points and involve independent third-party experts in site decisions to build public trust. All data and placement methodologies should be transparently published to demonstrate accountability and enable adaptive environmental management.

- **Establish comprehensive nitrogen guidelines for port industries:**
  Develop and strictly enforce mandatory nitrogen management standards covering all port-based industries, including fertiliser transshipment and storage, chemical processors, and logistics operators. These guidelines should set clear, science-based limits on nitrogen discharges, require detailed nutrient management plans, and mandate transparent, regular reporting (e.g., quarterly for industrial and port authority data, and annually for aggregated ecosystem-level indicators) of nitrogen and phosphorus inputs, outputs, and waste streams. This approach will reduce uncontrolled emissions, prevent water and air pollution, and ensure industries take full responsibility for their nutrient impacts.

- **Implement advanced wastewater treatment requirements:**
  Mandate the installation or upgrading of tertiary treatment systems for all port industries to ensure effective removal of nitrogen and phosphorus before any discharge into surrounding waters. Tertiary treatment systems are advanced wastewater treatment processes that remove nitrogen and phosphorus compounds after primary (physical removal of solids) and secondary (biological removal of organic matter) treatment stages. These systems may use biological nutrient removal processes, chemical precipitation, or membrane filtration. Set a clear, enforceable timeline for compliance, and offer targeted technical and financial support to help smaller operators meet these stricter standards. This approach will drastically reduce nutrient pollution, protect aquatic ecosystems, and align port operations with EU water quality directives.

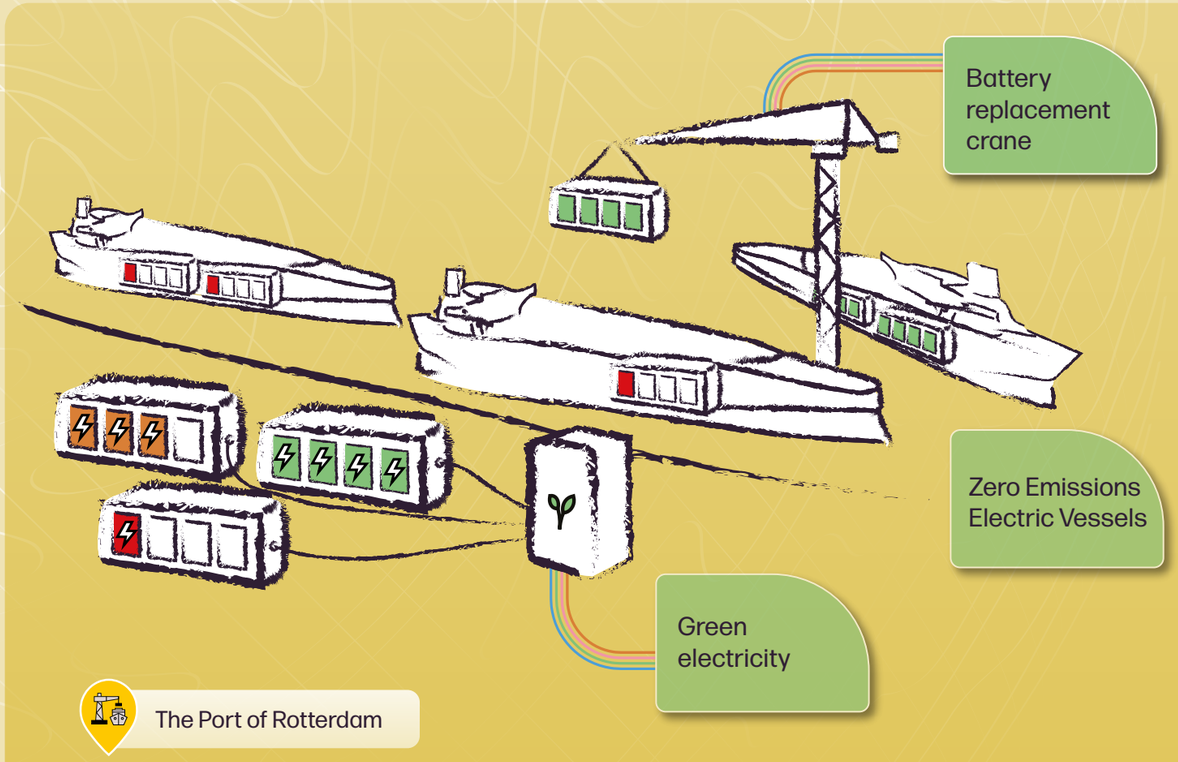
- **Manage nutrient loads through integrated stormwater and nature-based solutions:**
  Capture and treat nutrient-rich runoff before it reaches marine waters by installing bioretention systems, permeable pavements, and constructed wetlands across the port area to capture and treat nutrient rich runoff. Establish buffer zones of salt-tolerant vegetation around industrial zones, introduce floating treatment wetlands within harbor basins, and restore coastal habitats such as seagrass beds and salt marshes that act as a natural filter for phosphorus and nitrogen while enhancing marine biodiversity. Where feasible, route contaminated stormwater through dedicated drainage and treatment systems rather than allowing direct discharge to waterways.

- **Install emergency ammonia containment and treatment systems:**
  Ensure all ammonia wash systems and emergency sprinklers are connected to proper treatment infrastructure that can neutralise and process nitrogen compounds rather than releasing them directly into the environment. Develop rapid response protocols for nutrient pollution incidents and maintain real-time monitoring of emergency discharge systems.

- **Accelerate shore power infrastructure deployment:**
  Continue to expand shore power installations across all terminal types to enable ships to switch off diesel generators while berthed, effectively eliminating nitrogen oxide emissions at berth. This not only improves urban air quality but also prevents nitrogen deposition into coastal waters, reducing eutrophication and protecting marine ecosystems.

- **Establish incentives to increase shore power uptake:**
  Create strong incentive programmes to encourage shipping lines to actively use shore power connections and enter into off-take agreements, as low demand is the primary barrier to scaling shore power infrastructure. Promote the deployment of mobile shore power systems at terminals where permanent electrification is challenging or for berths serving smaller vessels[482], ensuring that all types of calls can benefit from cleaner, zero-emissions power while at berth.

- **Support ship hybridisation and battery solutions:**
  Accelerate the deployment of charging infrastructure for hybrid vessels equipped with battery packs, enabling them to power all hotel loads (all the electrical power needed to keep a ship operating while it is docked) cleanly during port stays. Continue to build partnerships and ventures such as Zero Emission Services[483] to develop battery swapping systems for vessels using modular or removable battery packs, and showcase the effectiveness of battery electric[484] and hybrid propulsion in cutting nitrogen emissions and overall pollution in port areas.



The Port of Rotterdam

Continue to build partnerships and ventures such as Zero Emission Services to develop battery swapping systems for vessels using modular or removable battery packs

Recommendations for Policymakers

- **Implement targeted measures to address NO_x pollution from shipping:**
  Strengthen IMO MARPOL Annex VI regulations by extending Tier III NO_x standards[485] to all vessel types and to operating areas, not just new ships in Emission Control Areas. Introduce not-to-exceed emissions limits specifically for engines running at low loads (below 25%), where NO_x emissions are highest. Mandate regular in-service compliance testing to ensure real-world performance, moving beyond reliance on initial certification alone. These measures will not only improve air quality but also significantly reduce marine nutrient pollution, protecting coastal ecosystems from algal blooms and hypoxia. These steps will close critical regulatory gaps, drive technological upgrades, and significantly reduce harmful nitrogen emissions from the shipping sector.

- **Ensure rigorous life cycle assessments for alternative marine fuels:**
  Require comprehensive well-to-wake evaluations that fully account for all nitrogen emissions across the entire fuel value chain, from production and transport to onboard combustion. Mandate that these lifecycle assessments (LCAs) explicitly include potential ammonia (NH_3) slip from ammonia-fueled vessels, nitrous oxide (N_2O) emissions from combustion of alternative fuels and indirect N_2O emissions from NO_x and NH_3 transformed in the environment. Even small releases of N_2O and NH_3 slip can ultimately contribute to marine nutrient loads, undermining efforts to protect coastal waters from eutrophication and biodiversity loss. This approach will prevent simply shifting nitrogen pollution from one stage to another, ensuring that new fuels deliver real, net environmental benefits rather than hidden trade-offs.

- **Integrate maritime nitrogen reduction with terrestrial restoration programmes:**
  Create policy frameworks that directly link reductions in shipping emissions to coastal and riverine restoration efforts. The Netherlands' "Room for the River" programme[486] has demonstrated how restoring floodplains along Rhine branches acts as a natural nitrogen sink through denitrification and sediment trapping. Similarly, restoring salt marshes[487] in the Wadden Sea and the Oosterschelde[488] estuary provides natural nutrient buffering capacity[489]. Establish mechanisms that encourage ports and shipping companies to support such restoration as part of their environmental strategies. Promote integrated approaches where nutrient recovery systems in ports supply reclaimed fertilisers for regenerative agriculture projects, closing nutrient loops and creating powerful circular economy synergies between maritime and land-based nitrogen management.

- **Strengthen degassing tank regulations and enforcement:**
  Mandate effective treatment for all ship tank cleaning operations, especially for vessels transporting fertilisers and nitrogen-based chemicals. Require port to provide sufficient reception and treatment facilities for contaminated tank washings, and implement real-time monitoring and detection systems to identify and prevent illegal discharges. Create strict, aligned global rules so operators cannot evade compliance by moving degassing operations to ports with weaker regulations. Preventing these direct discharges of reactive nitrogen is critical for protecting coastal ecosystems from eutrophication and maintaining the integrity of marine nitrogen cycles.

Conclusion and Call to Action

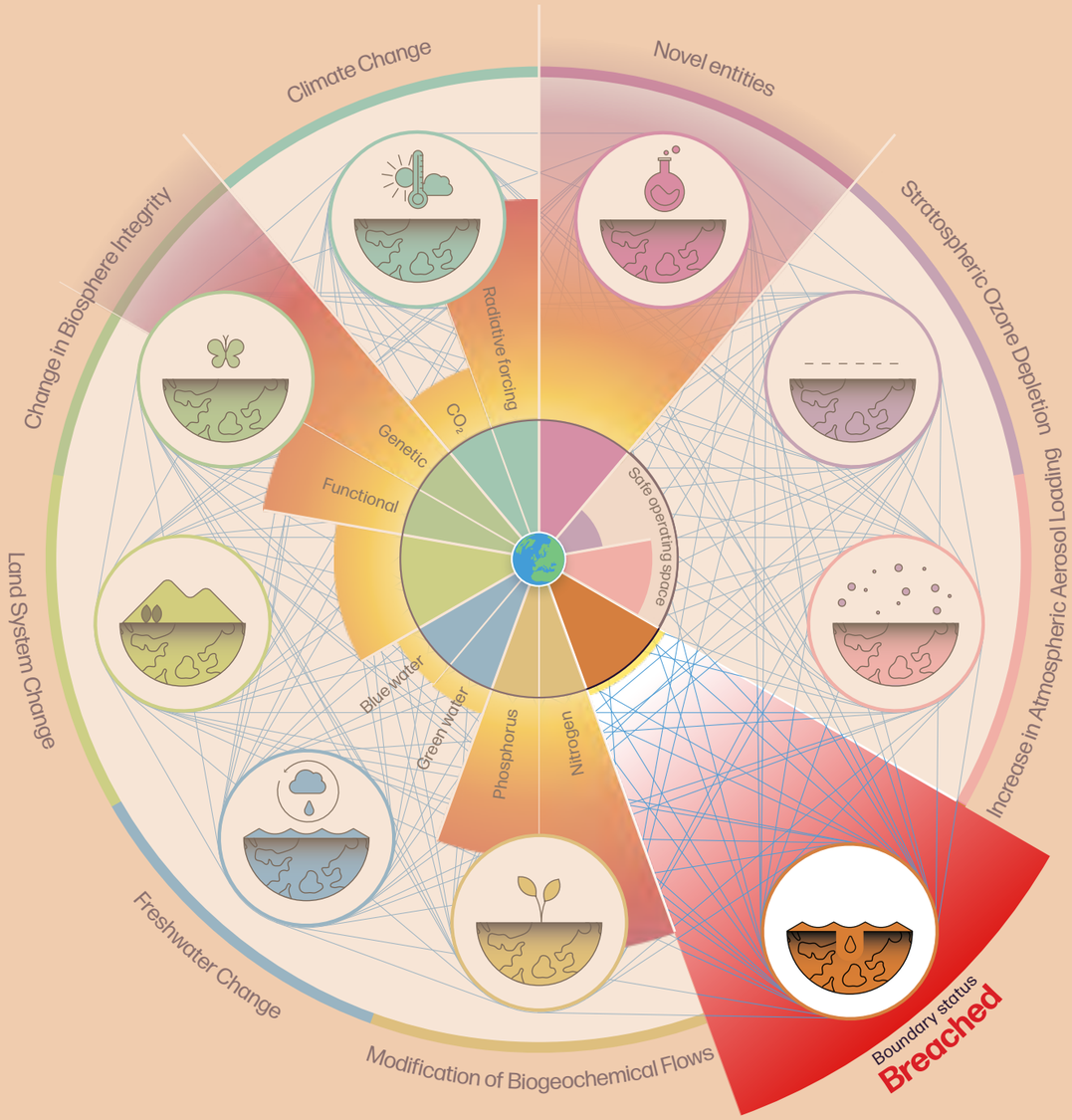
The biogeochemical flows boundary is one of the most dangerously and severely breached planetary limits, with devastating consequences for marine ecosystems and serious risks to the maritime economy. As Europe's largest port, Rotterdam sits directly at the crossroads of massive terrestrial nutrient surpluses and fragile marine ecosystem health.

Addressing this crisis demands a radical departure from traditional pollution control measures towards true circular economy approaches that treat nutrients as valuable resources, not disposable waste. By driving industrial symbiosis, aggressively investing in cutting-edge nutrient recovery technologies, and forging strong alliances with agricultural, industrial, and municipal partners, the port can show that large maritime hubs can actively reverse planetary boundary violations.

This approach will not only protect ecosystems and public health but also build long-term economic resilience and position Rotterdam as a true leader in sustainable maritime practice. The time to act boldly is now. The Port of Rotterdam and the city with their data, expertise, and understanding of the problem must embrace their roles as environmental stewards, leading by example to safeguard planetary health and secure a thriving, resilient maritime future.

"If we want to beat climate change, air pollution, water pollution, biodiversity loss, soil degradation and stratospheric ozone depletion, then a new focus on nitrogen will be vital."
Professor Mark Sutton,
Centre for Ecology & Hydrology (CEH)[490]

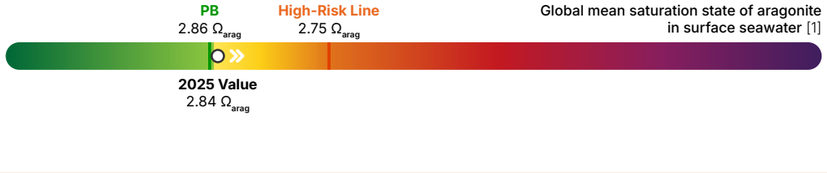
CH7 Ocean Acidification



CH2 Climate Change
CH3 Change in Biosphere Integrity
CH4 Land System Change
CH5 Freshwater Change
CH6 Modification of Biogeochemical Flows

CH7 Ocean Acidification
CH8 Increase in Atmospheric Aerosol Loading
CH9 Stratospheric Ozone Depletion
CH10 Novel Entities

Figure 7.1 Planetary Health Check 2025 status: Ocean Acidification



Source. *Planetary Healthcheck 2025*. CC BY 4.0.

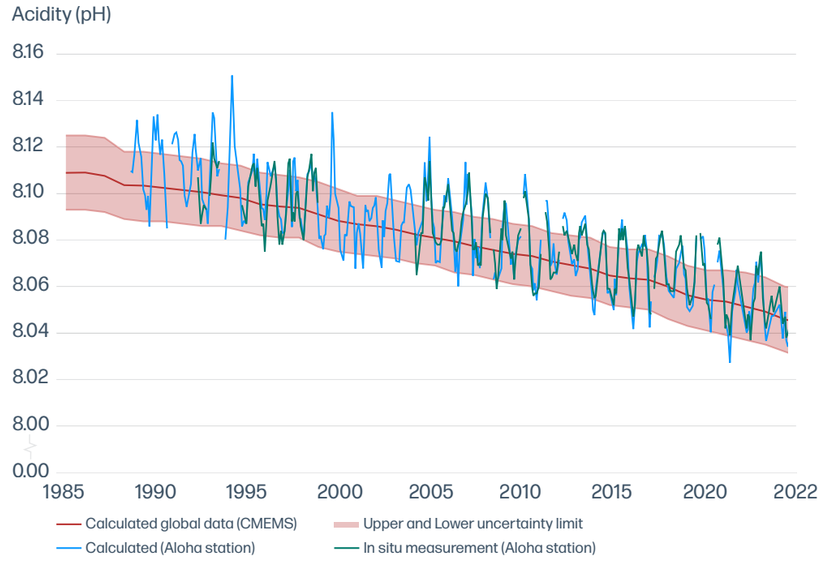
Introduction to the Boundary (Global)

Ocean Acidification (OA) is one of the most critical yet often overlooked planetary crises. OA is the increase in acidity (or decrease in the pH) of the Earth's oceans due to the absorption of atmospheric carbon dioxide (CO_2)[491, 492]. When CO_2 dissolves in seawater, it reacts to form carbonic acid, which then dissociates into bicarbonate and hydrogen ions. The increased concentration of hydrogen ions lowers the pH of seawater, making it more acidic.

pH indicates the basicity or acidity of a solution on a scale of 0 to 14, with pH 7 considered neutral. As the concentration of positively charged hydrogen ions in a solution increases, its acidity rises and pH decreases. A solution with a pH above 7 is basic (alkaline), while a pH below 7 is acidic[493].

The ongoing acidification of the ocean has **far-reaching harmful effects for marine ecosystems**[494], including weakened coral reefs, impaired shell formation in species like oysters and certain types of plankton, disruption of food chains, altered behavior and reproduction in fish and invertebrates, and serious risks to coastal communities that rely on fishing and aquaculture.The ocean absorbs ~ 30% of human-caused (anthropogenic) CO_2 emissions released to the atmosphere each year[495]. As a result, the average pH of seawater has dropped from 8.11 in 1985 to 8.04 in 2024 representing an 18% increase in acidity since 1985 and a 40% increase since pre-industrial times. If emissions continue, further decreases in pH are projected, posing severe risks to marine ecosystems, food security, and coastal economies worldwide[496].

Figure 7.2 Decline in ocean surface pH from global averages and in situ measurements at the Aloha station (1985–2022)



Source. European Environment Agency (2024), *Ocean acidification indicator*. Not covered by the OPP CC BY licence.

Within the Planetary Boundaries framework, the control variable for OA is the aragonite saturation state. Aragonite is a form of calcium carbonate used by calcifying organisms such as corals, mollusks, and certain plankton to build their shells and skeletons. The saturation state indicates whether seawater chemistry favours the formation of aragonite structures. Increased acidity reduces carbonate ion availability, lowering the aragonite saturation state – making it a reliable indicator of the severity of ocean acidification.

The planetary boundary for OA is set at an aragonite saturation of 2.86. The 2025 value is 2.84, which means that the ocean acidification boundary has now been breached[497].

CO_2 from human activities is the primary driver of OA. Therefore, CO_2 emissions from fossil fuels burned by vessels, and from industrial activities in and around ports contribute not only to climate change but also OA. In addition, oxides of sulfur and nitrogen released by ships can dissolve in seawater, forming sulfuric and nitric acids, which further exacerbate acidification and intensify stress on marine ecosystems[498].

If OA continues unabated, it will continue to have profound consequences for marine ecosystems and the vital services they provide to humanity including:

- **OA threatens global food security** by undermining marine protein supplies. In 2021, aquatic foods provided 3.2 billion people with at least 20 percent of their average animal protein intake, with even higher proportions in many poor countries[499].

- **Coral reefs are at risk of near-total collapse and mass mortality,** reducing natural coastal protection against storms[500] and increasing the costs of safeguarding coastlines through artificial infrastructure or restoration projects. Coral reefs provide coastal protection valued at more than US$ 4 billion per year globally, by reducing wave energy and preventing coastal erosion and flooding[501]. Additionally, tourism revenues are already declining in many regions due to reef degradation and coral bleaching, as seen in places like the Great Barrier Reef and parts of the Caribbean. Coral reef-related tourism currently generates approximately US$ 36 billion annually worldwide. If degradation continues, global tourism losses could eventually run into billions per year, severely impacting coastal economies and livelihoods[502].

- **Ocean biodiversity is at risk of dramatic declines and widespread species extinctions.** Clear evidence shows that many marine organisms are likely to suffer catastrophic impacts at projected future acidity levels, while a small number of opportunistic species may temporarily increase in abundance, often at the expense of overall ecosystem health and biodiversity. Shell-forming species such as oysters, mussels, crabs, clams, and lobsters will struggle to build and maintain their shells, threatening their survival. Populations of phytoplankton and algae will undergo dramatic shifts, disrupting species balance and triggering ripple effects throughout the marine food web, from declines in zooplankton and small fish to reduced numbers of large predators and severe impacts on fisheries and coastal communities. Ocean acidification can also alter fish behavior and impair reproduction, reducing overall fish populations. As a result, production from fisheries and aquaculture will decline, threatening livelihoods. Approximately 120 million people[503] depend directly on commercial capture fisheries value chains, with women constituting nearly half of this workforce, and the impacts will extend to coastal communities that depend heavily on these industries.

Marine organisms and ecosystems are shaped by complex interactions, such as adaptation, genetic diversity, and species relationships, which can either worsen or soften the effects of ocean acidification. In the Greater North Sea region, the surface ocean pH (a measure of acidity) is expected to decline by about **0.0023 units per year** under a medium-emission scenario (RCP4.5) and about **0.0036 units per year** under a high-emission scenario (RCP8.5)[504]. *(RCP stands for "Representative Concentration Pathway", scenarios used by scientists to model future greenhouse gas levels.)*

Although these numbers may seem small, they add up over decades and can make the ocean significantly more acidic, threatening the survival and growth of many marine species.

Similarly, the aragonite saturation state, which indicates how easily marine animals like corals and shellfish can build their skeletons and shells, is projected to decline by about **0.0093 per year** under RCP4.5 and **0.0156 per year** under RCP8.5. Aragonite saturation above 3.0 is needed to support healthy coral reefs and shellfish. As the saturation values fall, it becomes increasingly difficult for shell-building species to survive, leading to potential collapses of populations and major breakdowns across the marine food web.

The ocean naturally has a "buffering" ability that helps resist sudden changes in pH. Buffering is the ocean's natural chemical process, mainly involving dissolved carbonates, that helps stabilise pH by neutralising excess acidity when carbon dioxide is absorbed. In essence, buffering acts like a natural shock absorber, preventing the ocean from becoming too acidic too quickly. However, as the ocean continues to absorb large amounts of CO_2, this buffering capacity is weakening. A study in the U.S. found that the ocean's ability to buffer acidity could decrease by up to 34% between 2000 and 2100 under the high-emission scenario[505], making marine life even more vulnerable. This weakening buffer also means the ocean may become less effective at absorbing CO_2 in the future, potentially making climate change even worse. While these global ocean processes play out slowly and at large scales, coastal waters often face faster and more intense acidification driven by additional local factors.

Coastal waters can become more acidic due to local factors. For example, when algae and other organic matter decay, they release extra CO_2 into the water. Changes in wind and temperature can mix the water column and bring naturally more acidic deep water up to the surface. A process called upwelling can also push deeper, CO_2-rich water towards the coast. Coastal areas are especially vulnerable to acidification, but they are also very complex. Factors like temperature swings, river runoff, and high biological activity create constantly shifting conditions, making it difficult to fully understand acidification in these regions. To truly grasp how and why coastal acidification happens, and what it means for local marine life, researchers need detailed data collected over long periods and across many different sites[506].

It is crucial to ensure that measures to address OA are socially just and do not disproportionately burden vulnerable coastal communities, such as small-scale fishers and aquaculture workers. Addressing equity up front builds social support and ensures fair outcomes[507].

Table 7.1 Key drivers, impacts, and mitigation options for ocean acidification

OA Driver	Key Impacts	Primary Mitigation Options
CO_2 emissions from fossil fuels	Coral reef collapse, shellfish declines, biodiversity loss, fisheries impacts	Rapid emissions reductions at source, renewable energy transition. Nature-based solutions to support local adaptation.
Local nutrient runoff	Local acidification hotspots, harmful algal blooms	Improved wastewater treatment, agricultural best practices
Upwelling & mixing	Episodic low pH events on coasts	Local monitoring, ecosystem resilience measures

Source. One Planet Port Foundation (2026), OPP Vision Report synthesis.

Ocean acidification threatens marine ecosystems and interacts with other stressors to push systems towards collapse. While warm-water coral reef decline is primarily driven by thermal stress from ocean warming, acidification compounds the damage by weakening coral skeletons and inhibiting recovery. Deoxygenation – the loss of oxygen in marine environments—is an emerging threat often linked to warming and nutrient pollution, which can locally intensify acidification's effects in coastal waters.

These changes are closely linked to other planetary boundaries:

- **Climate Change,** since acidification, warming, and deoxygenation are all driven by rising atmospheric CO_2.
- **Biosphere integrity**, because acidification threatens calcifying organisms, disrupts marine food webs, and compounds other stressors affecting marine biodiversity.
- **Modification of Biogeochemical Flows,** as acidification alters carbon cycling between ocean and atmosphere, while excess nitrogen from shipping and other sources can exacerbate coastal acidification through eutrophication.

While ocean acidification is a global crisis, local contexts and national strategies shape how we respond. The following section highlights the situation in the Netherlands.

National Context: The Netherlands

The Netherlands' Climate Act, amended in 2023 to align with the EU Climate Law, sets legally binding targets: a 55% reduction in greenhouse gas emissions by 2030 (compared to 1990 levels) and climate neutrality by 2050. These targets represent increased ambition from the original 2019 reduction goals of 49% by 2030 and 95% by 2050[508].

However, current progress indicates that the country is not on track to fully meet these goals without significantly stronger policy effort[509]. It is crucial that policy and regulation are followed by concrete implementation, comprehensive monitoring, and robust analysis to ensure results, and to minimise unintended consequences, such as ecological harm to marine habitats, social and economic disruption to coastal communities, or overreliance on risky technological fixes. This is essential not only for addressing global warming but also its "evil twin": ocean acidification (OA).

The Netherlands adopted an OA Implementation Strategy in 2018[510]. Under the Dutch Marine Strategy (the national application of the EU Marine Strategy Framework Directive), ocean acidification is recognised as a major pressure. While pH is included in the regular monitoring programs, the strategy itself acknowledges that a second indicator (such as aragonite saturation) is urgently needed to adequately understand and track biological impacts, highlighting that current efforts are insufficient and must be expanded.

There is also an opportunity to integrate OA mitigation into broader EU policy frameworks, such as the EU Water Framework Directive and the European Green Deal's nature restoration law and zero pollution ambition. Including OA explicitly in these policies can help accelerate coordinated action. In addition to European frameworks, there are opportunities at the national level to integrate ocean acidification considerations into the Dutch Environment and Planning Act (Omgevingswet) and into port licensing conditions.

The North Sea, a shallow coastal sea, experiences acidification not only from atmospheric CO_2 but also from **seasonal changes in biological productivity** (the rate at which marine plants and algae produce organic matter through photosynthesis), river inputs, and inflows from the North Atlantic. To fully understand these complex, interacting processes, **long-term, continuous, and multi-parameter monitoring** is critical[511]. This includes tracking pH, carbonate chemistry (like aragonite saturation), biological indicators, and physical conditions over time and across different locations. The Royal Netherlands Institute for Sea Research (NIOZ)[512] contributes important data to the international Global Ocean Acidification Observation Network and regularly publishes detailed datasets from the Dutch North Sea. Such efforts are vital to measure progress and maintain urgency for action.

Policy and regulation must be matched by real implementation, rigorous monitoring, and robust analysis to deliver results and avoid unintended harm – especially as we confront not only climate change, but its 'evil twin': ocean acidification."

The total net emissions of the Netherlands in 2023 were 146.44 Mt CO_2[513]. The entire storage capacity of Porthos (37 Mt of CO_2) and the maximum storage potential of the gas fields of the Aramis project when fully available (400Mt CO_2)[514], can only store ~3 years' worth of emissions of the Netherlands.

Carbon capture and storage (CCS) is included in several emission reduction and net-zero scenarios. The Dutch government aims to cut **18 Mt* of CO_2** through CCS by 2030[515, 516†]. According to CIEL, offshore CCS remains unproven at scale, technically and environmentally uncertain, and a risky endeavour; nearly all past projects have faced unexpected problems or failed outright[517]. It should not be seen as a primary solution but rather as a last-resort measure to complement, not replace, drastic emissions reductions and expanded nature-based solutions (such as ecosystem restoration and blue carbon approaches).

In 2021, the Netherlands had 346 land-based companies dependent on North Sea fisheries, with a total turnover of EUR 6.6 Billion and 13,550 employees[518]. That same year, the Dutch-flagged fishing fleet had 720 vessels, with a combined gross tonnage of 99,440[519]. Domestic fish supply in the country has been declining at an average rate of 3.2% per year since 1965, and is projected to drop further to approximately 40,000 metric tons by 2028, down from around 45,000 metric tons in 2023. In contrast, fish consumption in the Netherlands is expected to continue rising, reaching about 146,000 metric tons by 2028, up from approximately 130,000 metric tons in 2023, representing an average annual growth rate of 1.9% since 2019[520]. This sharp drop in landings is primarily due to stricter catch limits, reduced fishing effort and declining fish stocks in the region. For example, North Sea fish landings have declined since 2020 to averaging around 1.6 million tonnes annually, down from peaks of 3-4 million tonnes in the 1960s and 1970s[521]. However, demand continues to grow and is increasingly met through imports and aquaculture.

* 1000 Mt = 1 Gt, 1 Mt CO_2 = 1000,000 metric tons of CO_2

† Page 38, "Indicatieve toedeling 49%-reductieopgave in 2030." [Indicative allocation of the 49% reduction target in 2030.] *https://open.overheid.nl/documenten/ronl-20f5fe94-8f10-4370-8488-8d3ba568bb4c/pdf*

Direct Impact of Ports and Shipping: Drivers and Consequences

Maritime transport and port operations contribute to ocean acidification through multiple pathways, both directly through CO_2 emissions and indirectly through other acidifying pollutants that compound the problem in coastal waters.

CO_2 Emissions from Shipping Operations: International shipping accounts for approximately 3% of global greenhouse gas emissions, currently producing over 900 million tonnes of CO_2 annually[522]. The ocean absorbs roughly 30% of anthropogenic CO_2 emissions, meaning that a substantial portion of shipping's emissions ultimately contributes to ocean acidification. While this CO_2 disperses globally through ocean circulation, shipping emissions are concentrated along major trade routes and in coastal waters near ports, creating regional acidification hotspots in areas with heavy traffic.

The maritime sector's emissions have grown significantly, increasing by 20% over the past decade[523], with a further 5% increase in 2024 alone[524] driven by vessel rerouting around geopolitical hotspots and increased speeds to maintain schedules. Despite growing recognition of the climate crisis, over 90% of the active global fleet by tonnage still operates on conventional fossil fuels, with only 8% of fleet tonnage equipped to use alternative fuels as of 2024[525]. Without decisive intervention, projections suggest emissions could surge by 90–130% by 2050[526], directly increasing ocean CO_2 absorption and accelerating acidification in coastal waters and along major shipping routes.

Sulphur and Nitrogen Oxide Contributions: Beyond CO_2, maritime emissions of sulphur oxides (SO_x) and nitrogen oxides (NO_x) create additional acidification pathways that are particularly problematic in coastal and port regions. When SO_x and NO_x are released from ship exhausts, they dissolve in seawater to form sulphuric and nitric acids – strong acids that directly reduce ocean pH[527].

Maritime emissions of sulphur oxides (SO_x) and nitrogen oxides (NO_x) create additional acidification pathways that are particularly problematic in coastal and port regions.

Research demonstrates that these acid-forming emissions cause regional pH reductions of the same order of magnitude as CO_2-driven acidification in heavily trafficked waters[528]. Studies have shown that acidification increases by 3–10% in certain coastal areas due to shipping-derived SO_x and NO_x deposition[529]. The calculated near-coastal seasonal acidification of 0.0015–0.002 pH units is significant, particularly because these strong acids also reduce the alkalinity of seawater, weakening the ocean's natural buffering capacity and making coastal waters more vulnerable to future acidification[530].

The impact is most pronounced in regions where approximately 85% of shipping emissions coincide with seasonal stratification in the water column[531]. This stratification concentrates the acid emissions within a relatively shallow surface mixed layer, intensifying local acidification effects. Coastal waters near major ports experience the most severe impacts due to the convergence of heavy shipping traffic, port operations, and industrial activities.

Port Industry Emissions: Port industrial complexes, particularly major hubs like Rotterdam, generate substantial direct CO_2 emissions from their operations and hosted industries. These emissions stem from multiple sources: cargo-handling equipment, truck and rail transport serving the port, power generation for port facilities, industrial processes in port-adjacent facilities (refineries, chemical plants, manufacturing), and the cumulative effect of vessels manoeuvring, berthing, and hotelling (running auxiliary engines whilst docked).

Ships at berth continue to emit pollutants whilst using auxiliary engines to power onboard systems, ventilation, cargo operations, and accommodation. Research examining ports across four continents found that Singapore, Rotterdam, and Antwerp ranked amongst the ports with the highest emissions from ships at berth[532]. Port operations that facilitate fossil fuel throughput—including storage, handling, and bunkering operations – contribute to both direct emissions from these activities and downstream emissions when these fuels are ultimately combusted.

Scrubber Discharge Complications: The exhaust gas cleaning systems (scrubbers) installed on ships to comply with sulphur emission regulations reduce atmospheric SO_x emissions, but transfer pollutants directly into seawater. Ships with closed-loop scrubbers can discharge approximately 126–150 cubic metres of acidic washwater directly into the marine environment daily[533]. Research demonstrates that this scrubber washwater is toxic to marine mesozooplankton communities even when diluted to 1.5% concentration[534]. Open-loop scrubbers, which account for over 80% of installations[535], continuously discharge large volumes of acidic washwater directly into the ocean during operations.

Seagoing vessels will soon be prohibited from discharging scrubber wastewater into all Dutch ports and inland waters. The OSPAR Ministerial meeting recently decided to ban open-loop scrubber discharges in internal waters and port areas throughout the North-East Atlantic (OSPAR Maritime Area) by July 2027[536]. Discharges from closed-loop scrubbers will be banned by January 2029[537].

Ballast Water Treatment By-Products: While ballast water management systems effectively prevent invasive species transfer, they generate disinfection by-products (DBPs) that contribute directly to ocean acidification[538]. A 2025 study shows that these DBPs can reduce ocean pH by approximately 0.057 units and carbonate ion concentrations by 24.06 µmol kg^{-1} per cubic metre of treated ballast water discharged. Given that ships globally discharge an estimated 10–12 billion tonnes of treated ballast water annually, the cumulative acidification impact in port waters is substantial. The IMO's Ballast Water Working Group has identified 41 high-priority DBPs requiring risk assessment due to their acidifying effects on seawater chemistry[539].

Cumulative and Synergistic Effects: The various acidification pathways from maritime activities interact synergistically with other stressors in coastal and port environments. Nutrient pollution from port runoff and ballast water discharge, heavy metal contamination from antifouling paints and industrial operations, and thermal pollution from cooling water discharge all compound acidification impacts on marine ecosystems. Ports represent convergence zones where multiple anthropogenic stressors concentrate, making these environments particularly vulnerable to acidification and creating conditions where even modest pH changes can trigger disproportionate ecological responses.

Coastal waters are already more variable and challenging for marine organisms due to natural fluctuations in temperature, salinity, and pH. The additional acidification pressure from shipping and port operations pushes these systems closer to ecological tipping points, threatening commercially important species such as bivalves, crustaceans, and fish populations that support regional fisheries and aquaculture.

The concentration of shipping emissions in coastal zones is particularly concerning given that these areas support the highest marine biodiversity and productivity while also providing critical ecosystem services such as fisheries, coastal protection, and carbon sequestration, upon which human communities depend. The Netherlands, with its extensive coastline and major port facilities, faces pronounced exposure to these maritime-driven acidification pressures in the North Sea.

Nutrient pollution from port runoff and ballast water discharge, heavy metal contamination from antifouling paints and industrial operations, and thermal pollution from cooling water discharge all compound acidification impacts on marine ecosystems.

Solutions and Maritime Interventions

The most effective and immediate way to mitigate OA is to dramatically reduce activities that produce CO_2 emissions in the first place, such as fossil fuel combustion, intensive industrial shipping, and deforestation. This direct reduction is more direct and reliable than speculative technological fixes.

Measures focused on reducing other greenhouse gases, such as methane and nitrous oxide, are important for addressing atmospheric warming but do not directly help with OA, since CO_2 is the primary driver of ocean acidification[540]. The relationship between OA and nitrous oxide is complex and nuanced[541]. Moreover, as the water in the ocean circulates and mixes very slowly, even if we stopped all CO_2 emissions today, the CO_2 already absorbed in the ocean would continue to acidify seawater for decades to centuries to come[542].

In addition, international frameworks such as the International Maritime Organization's (IMO) climate strategy encourage a transition to low- and zero-carbon marine fuels. Supporting this transition helps reduce both CO_2 and sulfur and nitrogen oxide emissions, addressing ocean acidification and air pollution simultaneously. Examples include the development of shore-side infrastructure for green methanol bunkering (e.g., Maersk's green methanol-ready ships), hydrogen-based fuel hubs, shore power (cold ironing) to allow ships to shut down engines while at berth, battery-electric vessels for short-sea and inland shipping, and wind-assisted propulsion technologies, such as rotor sails and wing sails, which can significantly cut fuel use.

Various ocean-based Carbon Dioxide Removal (CDR) approaches are being explored as potential ways to help mitigate ocean acidification (OA). CDR refers to methods designed to actively remove CO_2 from the atmosphere and store it for long periods, often by enhancing ocean uptake. While these methods do not remove CO_2 already present in ocean water directly, they aim to lower atmospheric CO_2 levels, which in turn can help slow future ocean acidification.

These ocean-based CDR approaches include protecting and restoring blue carbon ecosystems (such as mangroves, salt marshes, and seagrasses), which naturally capture and store carbon in plant biomass and sediments. They also include more experimental and largely untested techniques, such as enhancing ocean alkalinity (adding crushed minerals to make seawater absorb more CO_2) and farming and sinking macroalgae (growing seaweed in the ocean and then sinking it to deep waters to try to lock away carbon for centuries).

Except for a few blue-carbon methods, most of these ocean CDR techniques, especially the engineered or "geoengineering" (involve human-made, large-scale technological changes to ocean systems) approaches, are still conceptual[543], unproven at scale, typically costly, and carry significant ecological risks and uncertainties. Their economic viability is also currently highly dependent on subsidies[544]. The impacts vary considerably depending on the specific method and materials used. For instance, some alkalinity enhancement approaches using sodium hydroxide have shown negligible effects on phytoplankton communities in experiments, other approaches using crushed minerals like olivine have disrupted plankton communities, particularly affecting cyanobacteria and other key primary producers[545]. Potential side effects that require careful assessment include harmful algal blooms (with ocean acidification already shown to promote certain toxic algal species)[546], oxygen depletion in subsurface waters, shifts in marine food webs, toxic effects from trace metals contained in alkaline minerals, changes in nutrient cycling and availability, and unforeseen impacts on biodiversity[547]. The biological and ecological repercussions of large-scale alkalinisation remain largely unknown, creating substantial uncertainty about environmental consequences. Major challenges need to be addressed for ocean carbon removal, including insufficient governance, a small knowledge base, underdeveloped monitoring and verification processes, and uncertain environmental and social impacts[548]. In the meanwhile, they may be an economic and intellectual distraction from more relevant efforts to reduce CO_2 emissions.

Table 7.2 Summary of ocean-based carbon dioxide removal (CDR) methods compared with direct emissions reduction

CDR Method	Potential Scale	Cost	Duration of Storage	Technical Readiness	Key Risks	Key Benefits
Blue Carbon	0.008-0.3 $GtCO^2$/yr for mangroves/salt marshes; 0.02-0.3 GtC/yr for whale/ fish population rebuilding	$37-$1,800/ton C for mangroves; $17-$40,820/ ton C for other methods	Centuries for coastal ecosystems; >100 years for deep ocean carbon	High for mangroves/salt marshes; Low for seagrass restoration	Uncertain MRV; Methane emissions from some ecosystems	Coastal protection; Increased biodiversity; Food security; Support for livelihoods
Macroalgal Mariculture and Sinking	0.3 $GtCO_2$/yr would require ocean area the size of Kentucky	~$2,050/ton C (current); $275/ ton C (DOE goal)	>500 years if sunk below 1,000m	Medium for farming; Low for deep-sea sinking	Oxygen depletion in deep sea; Marine mammal entanglement; Competition with other marine uses	Potential job creation; Co-location with renewable energy; New habitat creation; Nutrient remediation
Ocean Fertilisation	1 $GtCO_2$/yr most likely (range <1-5 GtC/yr)	<$50/ton CO_2	10-100 years average	Medium (field experiments confirm blooms but uncertain carbon storage)	Potential nutrient robbing; Harmful algal blooms; Water column acidification; Low-oxygen zones	Possible increased fish populations; Low cost
Ocean Alkalinity Enhancement	~2 $GtCO_2$/yr	$70–$120/ ton CO_2 for carbonates	Depends on water column physics, chemistry, and biology. >100 years in some cases	Medium (chemistry well-established, logistics challenging)	Mining impacts; Toxic metal release; Phytoplankton species shifts	Decreases ocean acidification; May benefit marine life with shells
Electrochemical Methods	0.001-0.002 $GtCO_2$/yr would require water volume equal to all desalination plants worldwide	Not specified	Not specified	Low (prototype scale only)	Seawater intake risks to marine organisms; Local pH changes	Potential co-benefits like hydrogen production
Sub-seafloor Geologic Storage	Prudent planetary limit is 1,460 Gt. Technical potential for geologic carbon storage is commonly assumed to be vast, with estimates of available storage of around 10,000–40,000 Gt CO^2 in the scientific literature. Industry estimates are around 14,000 $GtCO^2$, of which 13,400 $GtCO^2$ is undiscovered and just 253 $MtCO^2$ is considered currently economically viable.[549]	Higher than onshore storage	Extremely durable (10,000+ years with <0.001% leakage/yr)	Medium-High (successfully demonstrated in small-scale projects)	CO_2 leakage during transport or storage; Potential harm to marine organisms	Longest sequestration timescales of any ocean-based CO^2 storage method
Emissions Reduction	Unlimited (theoretically the largest impact if fully implemented across all sectors)	Generally the lowest-cost approach per ton CO_2 when including avoided damages and co-benefits; varies widely by sector and policy.	Permanent (as emissions are prevented from entering the atmosphere and ocean in the first place)	Very high (technologies and practices already exist and are deployable immediately)	Political and economic resistance; social inequality if poorly designed; potential rebound effects if not paired with absolute activity reductions.	Immediate climate and ocean acidification mitigation; supports biodiversity; reduces air pollution; improves human health; strengthens long-term ecological and economic resilience.

Note. This overview is focused on ocean-based CDR methods only.

Source. One Planet Port Foundation (2026), based on Ocean Conservancy (2023), *Ocean Carbon Dioxide Removal Methods*. Not covered by the OPP CC BY licence where third-party content applies.

While some propose Carbon Capture and Storage (CCS) in geological formations (including under the seabed) as a complement to emission reductions, CCS faces fundamental limitations. A 2025 analysis in Nature established a prudent planetary limit of approximately 1,460 Gt of CO_2 for geological storage after accounting for geophysical, environmental, human health, and policy risks – an order of magnitude lower than commonly cited technical potential estimates[550]. Nearly all climate scenarios would exceed this prudent storage limit before 2200, and using the full storage potential for carbon removal would cap possible global temperature reduction to only 0.7°C[551]. Risks include potential CO_2 leakage and localised groundwater acidification, though well-regulated storage can retain over 98% of CO_2 over 10,000 years[552]. Rather than relying on CCS as a primary strategy, rapid, large-scale emissions reductions and nature-based solutions should be prioritised.

It is often cited that 7,000–9,000 Mt of CO_2 per year will need to be removed globally by mid-century to meet the 1.5°C Paris Agreement target[553]. While this is primarily framed in terms of reversing climate change, it is also relevant for OA, since CO_2 drives both problems. However, given the slow ocean response, even achieving this level of removal will only slow, not fully reverse, acidification trends within this century[554]. In 2025, atmospheric CO_2 levels have already reached an average of 423 parts per million (ppm)[555], peaking at 430.5 ppm in May[556].

Unlike climate change, there is no globally agreed-upon "ocean acidification reversal" target expressed in tons of CO_2 removal. However, scientists know that to stabilise ocean pH and halt further acidification, atmospheric CO_2 would need to return to around pre-industrial levels of approximately 280 ppm. Humans have emitted over 1.5 trillion tons of CO_2[557, 558] since then.

To put this into perspective:

- Returning to 350 ppm (sometimes cited as a safer climate stabilisation level) would require removing hundreds of billions to potentially over a trillion metric tons[559, 560, 561] of CO_2 from the atmosphere, accounting for carbon cycle feedbacks that reduce removal efficiency, an almost unimaginable scale.

- Around 7–9 billion metric tons (Gt) of CO_2 per year would need to be removed globally by mid-century just to stay on track for the 1.5°C Paris Agreement target[562] and even more to begin reversing OA trends.

Cutting emissions deeply and rapidly is far more reliable and equitable than relying on speculative, costly, and high-risk technological fixes. Restoring natural systems, such as forests, wetlands, and marine ecosystems, can play a supporting role, but these must accompany, not replace, urgent emission reductions.

Current Contributions and Facts from the Port of Rotterdam

The Port of Rotterdam, Europe's largest seaport, directly contributes to ocean acidification by emitting approximately 20.2 million tonnes of CO_2 per year from its port and industrial complex[563], equivalent to around 13–15% of total Dutch national emissions[564, 565].

In addition, the port facilitates the trade and transport of fossil fuels and bulk goods that physically pass through its terminals and facilities, handled by companies for which the port acts as landlord and service provider. When these fuels are eventually burned elsewhere, a large share of the resulting emissions is absorbed by the ocean, directly accelerating acidification both locally and globally. About 30% of all these emissions are ultimately absorbed by the ocean[566], directly accelerating acidification both locally and globally. Direct and downstream emissions represent a significant share of the Netherlands' total carbon footprint and underscore the Port of Rotterdam's outsized role as a global emissions hub. This highlights the port's critical responsibility in addressing both climate change and ocean acidification.

The Porthos project in the Port of Rotterdam, with construction underway since 2024, is planned to launch in 2026[567] and aims to store about 37 million tonnes of CO_2 over 15 years[568] in depleted gas fields under the North Sea. This project has been allocated up to €2.1 billion in SDE++ subsidies (as a maximum budget reservation over 15 years) from the Dutch government for the four industrial customers. The actual subsidy amount paid will likely be lower, as in practice, the government only covers the difference between CCS costs and EU emissions trading prices[569], effectively de-risking the investment for private industry regardless of carbon price fluctuations. The funding will be cancelled when ETS rates surpass CCS costs per unit.

Similarly, the Aramis project[570] (for additional CO_2 storage in North Sea gas fields) and CO_2Next (a planned liquefied CO_2 terminal at the 2nd Maasvlakte) are scheduled to become operational by 2029-2030[571]. These projects also rely on significant public funding support, likely into the hundreds of millions to proceed; nearly €800 million confirmed between EU[572] grants and Dutch[573] government commitments .

While these carbon capture and storage (CCS) projects are presented as flagship climate solutions, they remain undertakings that face significant uncertainties regarding performance at this magnitude, long-term storage monitoring requirements, and the complexities of integrated transport infrastructure. The heavy reliance on public funds raises concerns about diverting resources away from proven, immediate solutions like direct emissions reductions and ecosystem restoration.

As these projects develop, it is crucial to implement robust and transparent monitoring plans, tailored to each project's specific risks, and to integrate collected data into predictive models. Continuous, multi-disciplinary research is needed to ensure compliance with safety and environmental standards and to avoid unintended consequences, such as potential CO_2 leakage or marine ecosystem disruption.

Beyond CCS, the port and its industrial partners have a critical responsibility to reduce emissions at source and adopt nature-based solutions as a priority.

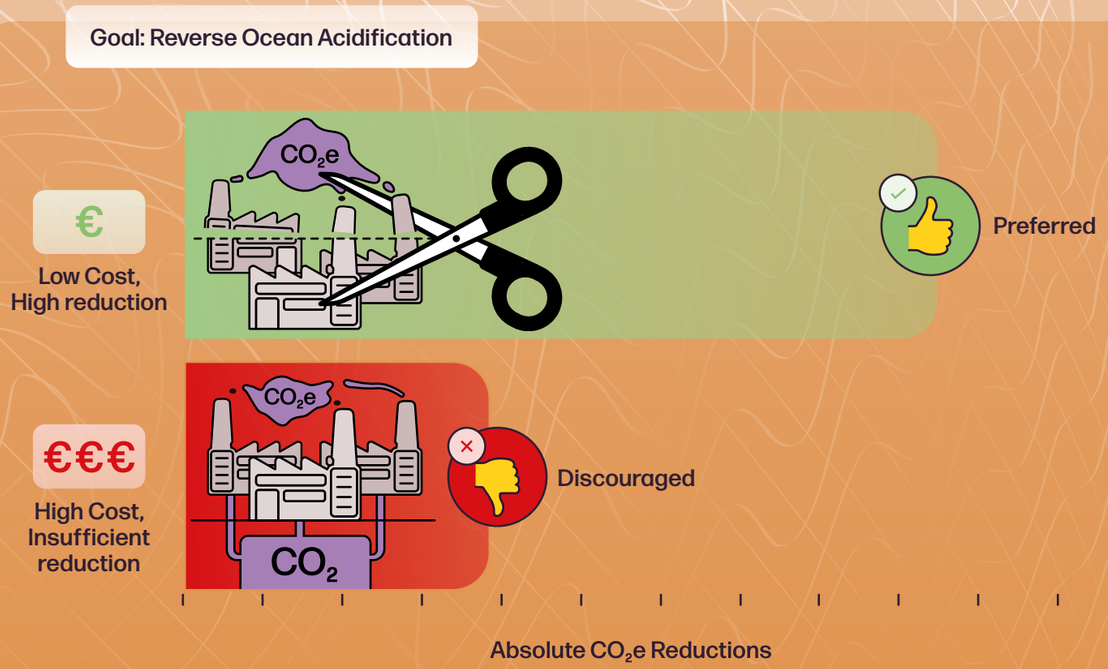
Note: General CO_2 emissions reduction efforts of the Port of Rotterdam are addressed in the Climate Change chapter.

Recommendations for the Port of Rotterdam

- **Accelerate infrastructure for low- and zero-carbon shipping fuels:**
  Accelerate infrastructure for low- and zero-carbon shipping fuels (such as green methanol, hydrogen, green ammonia with strict emission controls) and expand support for battery-electric vessels on short-sea and inland routes. Prioritise green fuel bunkering that reduces both CO_2 and co-pollutants (NO_x, SO_x), addressing climate change and ocean acidification simultaneously.
- **Prioritise emissions reductions at source:**
  Prioritise emissions reductions at source by supporting electrification of port equipment, expansion of shore power (cold ironing), and modal shift to rail and inland shipping.
- **Transition away from fossil fuel throughput:**
  Transition away from fossil fuel throughput by phasing out terminal leases and subsidies for coal, LNG, and oil-related activities. Reallocate space towards low-carbon logistics, circular industries, and green hydrogen infrastructure.
- **Invest in marine ecosystem restoration:**
  Invest in marine ecosystem restoration efforts, such as seagrass beds and oyster reefs, to enhance local carbon storage and resilience to acidification.
- **Prioritise proven port-wide mitigation strategies:**
  Focus on established mitigation strategies, including port-wide energy efficiency programs and green shipping corridors, over unproven or high-risk technologies.
- **Ensure robust oversight of CCS and CDR pilots:**
  Require all CCS and CDR pilot projects hosted in the port to include independent monitoring, public access to data and a clear exit strategy if ecological or social risks outweigh anticipated benefits.
- **Expand transparency on Scope 3 emissions:**
  Increase transparency and reporting on Scope 3 emissions facilitated by the port and disclose full CO_2-equivalent flows, including import, export, bunkering and storage.
- **Integrate ocean acidification criteria into permitting:**
  Include explicit OA-related criteria in environmental permits and licensing to ensure that port activities, industrial emissions, and coastal developments account for acidification impacts and adopt mitigation measures.

Recommendations for Policymakers

- **Introduce ocean acidification indicators into environmental law:**
  Embed specific ocean-acidification indicators and thresholds into regional and national environmental legislation, for example by incorporating aragonite saturation state into Marine Strategy Framework Directive implementation.
- **Prioritise absolute CO_2e reductions in ocean acidification responses:**
  Place absolute CO_2e emissions reductions at the center of OA policy responses, avoiding overreliance on unproven, high-cost carbon removal strategies that delay meaningful mitigation.



Global issue

Address ocean acidification by prioritising absolute CO_2e reductions over energy- and resource-hungry carbon removal strategies that crowd out effective mitigation.

- **Integrate ocean acidification into climate impact assessments:**
  Ensure that climate impact assessments for new infrastructure explicitly account for ocean acidification, especially in marine and port zones.
- **Support a just transition for fisheries and coastal communities:**
  Provide a Just Transition for fisheries and coastal communities by providing financial, technical, and adaptation resources for those most vulnerable to OA impacts.
- **Mandate rigorous oversight of ocean-based CDR and CCS projects:**
  Require robust monitoring, verification and public reporting for all ocean-based CDR and CCS projects, along with full lifecycle analysis covering material–energy balance, ecological risks and planetary-boundary implications.
- **Support IMO Risk Assessments for ballast water disinfection by-products:**
  Assist with the completion of IMO risk assessments for high-priority ballast-water disinfection by-products and establish discharge standards that balance invasive-species prevention with coastal acidification mitigation.
- **Direct public funding toward multi-benefit solutions:**
  Channel public funding toward solutions that benefit multiple planetary boundaries, prioritising nature-based interventions, circular-economy approaches and proven, community-led climate actions with transparent monitoring.
- **Accelerate maritime decarbonisation to reduce ocean acidification drivers:**
  Advance maritime-sector decarbonisation to reduce the shipping industry's contribution to atmospheric CO_2 and ocean uptake. Align with international frameworks such as the IMO's greenhouse gas strategy, prioritizing zero-carbon fuels that also reduce co-pollutants (NO_x, SO_x) affecting ocean chemistry.
- **Establish adaptive regulation for emerging ocean risks:**
  Develop adaptive monitoring and regulatory frameworks for emerging threats including seabed-mining impacts, seafloor methane releases, and shipping disturbances, with mechanisms to update requirements as scientific understanding evolves.
- **Reduce land-based stressors that exacerbate acidification:**
  Decrease land-based stressors (nutrient runoff, pollution) that compound OA impacts on marine ecosystems, particularly in coastal zones where acidification effects are most severe.
- **Incorporate marine spatial planning to Protect Ocean Acidification Refugia:**
  Integrate marine spatial planning that identifies and protects OA refugia—areas with naturally higher pH or buffering capacity – to support ecosystem resilience and adaptation.
- **Increase research funding for ecological and biological adaptation:**
  Boost research investment for biological and ecological adaptation strategies, including selective breeding programs for commercially important species and restoration of calcifying habitats (oyster reefs, cold-water corals).
- **Highlight and account for co-benefits of ocean acidification mitigation:**
  Emphasise and account for co-benefits of OA mitigation actions, including improved air quality, enhanced coastal protection, biodiversity gains, and stronger community resilience.

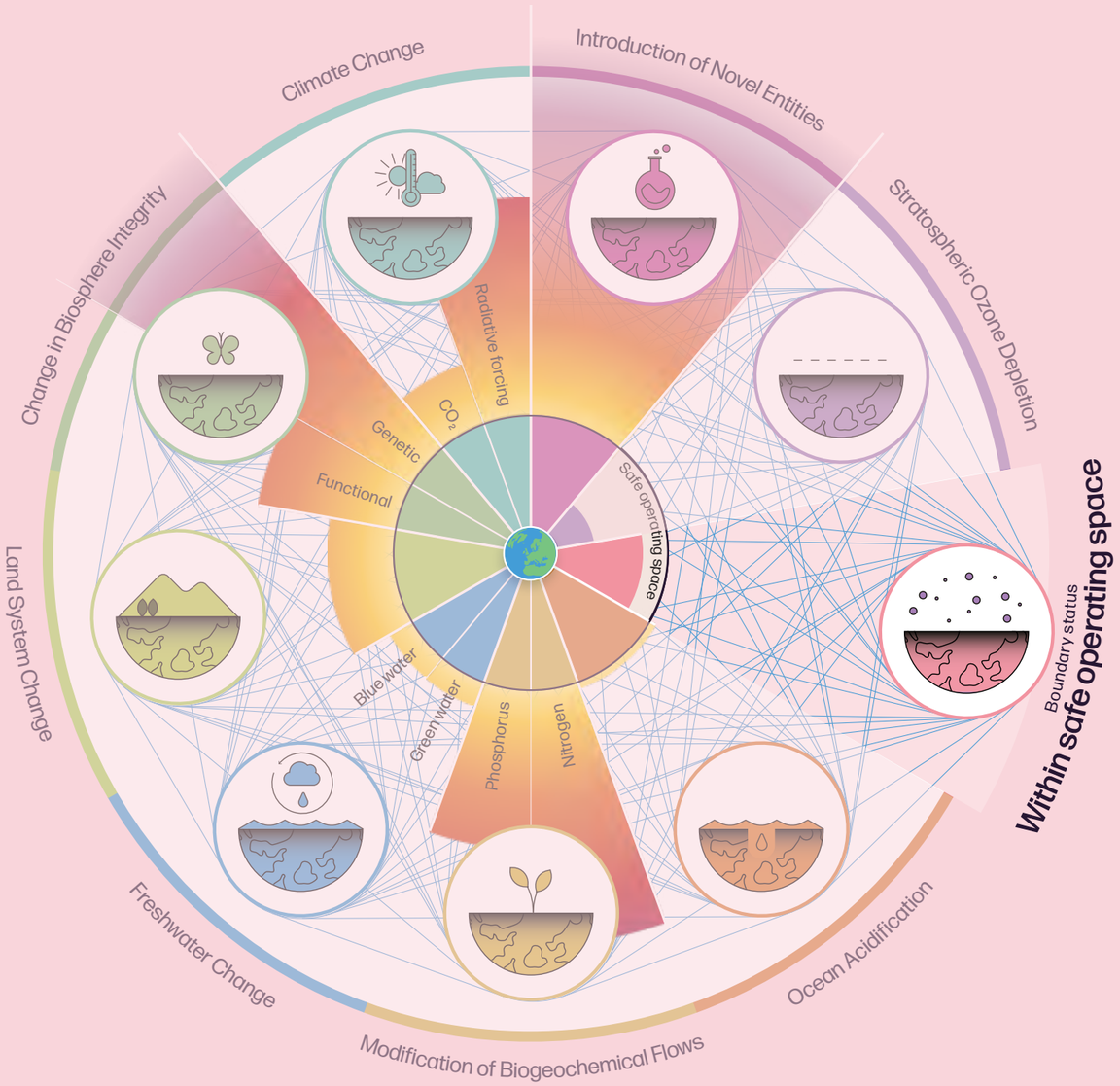
Conclusion and Call to Action

Ocean Acidification represents a silent but severe threat to marine life, coastal economies, and food security worldwide.

The science is clear: drastic and immediate reductions in CO_2 emissions are the most reliable and fair pathway to address both climate change and ocean acidification. Nature-based solutions and equitable approaches must lead, supported by strong monitoring, transparent governance, and transformative changes in sectors like shipping and ports. The Port of Rotterdam, and similar global hubs, have a responsibility to act as catalysts for a just, rapid transition towards a regenerative, ocean-positive future.

"Ocean acidification isn't just an environmental crisis – it's a ticking time bomb for marine ecosystems and coastal economies."
Professor Steve Widdicombe, co-chair of the Global Ocean Acidification Observing Network

CH8 Increase in Atmospheric Aerosol Loading



CH2 Climate Change
CH3 Change in Biosphere Integrity
CH4 Land System Change
CH5 Freshwater Change
CH6 Modification of Biogeochemical Flows
CH7 Ocean Acidification
CH8 Increase in Atmospheric Aerosol Loading
CH9 Stratospheric Ozone Depletion
CH10 Introduction of Novel Entities

Figure 8.1 Planetary Health Check 2025 status: Increase in Atmospheric Aerosol Loading

Source. *Planetary Healthcheck 2025*. CC BY 4.0.

Introduction to the Boundary (Global)

Aerosols are small particles suspended in the atmosphere. Aerosols range in size from a few tens of nanometers, less than the width of the smallest viruses, to several tens of micrometers, about the diameter of human hair[574]. The size and composition of aerosol particles affects how far they can travel around the world, their interactions with solar and thermal radiation, and their potential effects on health.

Natural sources of aerosols include volcanoes, sea spray and mineral dust. Industrial aerosols from human activities primarily include[575]:

- Sulfates, which are produced when sulfur dioxide (SO_2) reacts with water vapor and other gases in the atmosphere. One source of this is the burning of coal and fossil fuels in power generation and industry;
- Nitrates, which are most often formed when combustion engines (such as vehicles, shipping, and power plants) release nitrogen oxides (NO_x). These react in the atmosphere to form nitric acid which then combines with ammonia (NH_3) which often originates from agriculture, to form ammonium nitrate – the dominant pathway for nitrate aerosol formation[576];
- Organic and black carbon, also largely emitted by combustion processes, including biomass burning, diesel engines, and residential solid fuel use (e.g., wood, crop waste, charcoal, coal).

Aerosol particles are categorized by their aerodynamic diameter*, PM_{10} (10 micrometers or less), $PM_{2.5}$ (2.5 micrometers or less), and ultrafine particles (UFPs), also called nanoparticles, with diameters of 0.1 µm (100 nanometers) or less. Particle size determines where they deposit in the respiratory tract and how they interact with the body. Ultrafine particles are particularly concerning[577] because their small size allows them to penetrate deep into the lungs, pass into the bloodstream, and reach organs such as the heart and brain. Their large surface area makes them highly reactive and capable of carrying toxic compounds. UFPs are ubiquitous in urban environments, especially near roads, ports, and airports, meaning populations are chronically exposed even when mass concentrations of $PM_{2.5}$ appear moderate.

The planetary boundary for atmospheric aerosol loading is measured using aerosol optical depth (AOD), which represents the reduction in sunlight reaching Earth's surface due to scattering and absorption by aerosol particles in the air column[578].

The boundary is defined globally as an interhemispheric difference in AOD of 0.1, with a pre-industrial baseline of 0.04. In other words, if the difference between the Northern and Southern hemispheres exceeds 0.1, it signals a transgression of the safe operating space. The observed difference in 2025 was 0.063, and trending downward, meaning the boundary is currently within the safe range[579]. A rising interhemispheric AOD difference can lead to shifts in monsoonal patterns and affect weather cycles, increasing the risk of floods and droughts.

* PM = Particulate Matter

However, this global framing masks dangerous regional deviations based on local conditions[580]. Regionally, AOD often correlates with $PM_{2.5}$ concentrations, which are critical for human health. But the planetary boundaries framework does not yet fully integrate these regional health risks[581], nor does it adequately account for ultrafine particles, which may cause disproportionately large health impacts despite contributing little to overall AOD or $PM_{2.5}$ mass.

Not addressing aerosol pollution can have several cascading effects on human health and the economy:

- **Damage to the economy:** In the European Union, air pollution still causes an estimated €600 billion in losses annually (around 4% of EU GDP). These losses stem from increased absenteeism, productivity declines and harm to ecosystems[582]. Absenteeism can be caused by respiratory and cardiovascular illnesses linked to pollution exposure. In-job productivity would also decrease, as workers with chronic exposure are likely to experience fatigue, reduced cognitive performance, and have greater susceptibility to illness[583]. The EU's 10% most-polluted regions suffer 25%of the burden of mortality attributable to air pollution[584]. Air pollution is closely linked to climate change and harms vital ecosystems, causing global crop yield losses of 3-16%[585], further threatening economies.

- **Damage to human health:** Outdoor air pollution is classified as a carcinogen or a cancer-causing substance[586]. Poor air quality can contribute to lung cancer, asthma, stroke, heart disease, pregnancy complications[587], and emerging research suggests links to mental health issues, including Parkinson's disease, Alzheimer's disease, other forms of dementia, and depression and anxiety disorders[588]. In India, nearly 2.18 million deaths per year are attributed to air pollution, second only to China with 2.44 million deaths per year[589]. The University of Chicago's Air Quality Life Index estimates that 510 million people in northern India may lose an average of 7.6 years of life expectancy if current trends continue[590]. Comparable studies in Europe estimate that around 300,000 premature deaths occur annually across the EU[591] as a direct result of particulate pollution, making it one of the leading environmental health risks on the continent.

The World Bank estimated that the global health damages of ambient air pollution were between $4.5–$6.1 trillion a year, or about 4.7%–6.5% of global GDP in 2020, due to premature death, lost labor, productivity, and reduced life expectancy[592]. The same report projected that air pollution deaths would increase from 5.7 million in 2020 to 6.2 million by 2040 if countries only implement their current commitments, despite these policies reducing emissions by 6%. The increase is driven by population growth and economic development in high-pollution regions. However, implementing integrated policies (combining air quality management with climate/energy measures) could reduce air pollution deaths to 4.1 million per year by 2040, representing a 35% reduction.

Table 8.1 Main health and environmental impacts associated with key air pollutants

Pollutant	Effects proven and included	Effects probable but not included
$PM_{10}/PM_{2.5}$	All-cause mortality	Medication use
	Acute mortality	Lower respiratory symptoms
	Infant mortality	Diabetes
	Workdays loss	
	Restricted activity days	
	Chronic bronchitis	
	Respiratory hospital admission	
	Cardiovascular hospital admissions	
Ozone	Acute mortality	Chronic mortality
	Respiratory hospital admission	Workdays loss
	Cardiac hospital admissions	
	Restricted activity days	
	Increased mortality risk	
NO_2	Bronchitis in asthmatic children	Cardiovascular effects
	Respiratory hospital admissions	Acute mortality

Source. Oliu-Barton, M. & Lopez, J.M. (2024), *How much does Europe pay for clean air?*, Bruegel Working Paper 15/2024. Not covered by the OPP CC BY licence.

Increase in Atmospheric Aerosol Loading impacts several of the other boundaries through complex interactions:

Climate Change: Aerosols influence Earth's energy balance by scattering sunlight (cooling) or absorbing it (warming)[593]. Darker aerosols like black carbon absorb more solar radiation, leading to warming. Lighter aerosols like sulphates reflect more sunlight, leading to cooling[594]. They also modify cloud properties, altering radiative forcing and temperature patterns[595].

Freshwater Change: Aerosols can serve as cloud condensation nuclei (CCN), tiny particles around which water vapour condenses to form cloud droplets[596]. Without these particles, water vapour alone has difficulty condensing in the atmosphere. Changes in the number and type of CCN influence how many droplets form, their size, and ultimately the amount and distribution of rainfall. This means high aerosol concentrations can suppress rainfall in some regions while intensifying it in others.

Biosphere integrity: Aerosols can damage the surface of leaves when they come into contact with them and also change the amount of sunlight reaching leaves, impacting photosynthesis levels[597]. Acid rain from sulphate and nitrate aerosols acidifies soils and freshwater ecosystems, damaging forests, lakes, and streams[598].

National and Local Context: The Netherlands and Rotterdam

In December 2024, the European Commission's revised Ambient Air Quality Directive (AAQD)[599] entered into force. This is a milestone for the European Green Deal's zero-pollution ambition of achieving a non-toxic environment by 2050[600]. This updates air quality standards, lowering the allowable levels for twelve pollutants: particulate matter ($PM_{2.5}$ and PM_{10}), nitrogen dioxide (NO_2) and nitrogen oxides (NO_x), sulphur dioxide (SO_2), ozone (O_3), carbon moNO$_x$ide, benzene, benzo[a]pyrene, arsenic, cadmium, nickel, and lead. EU member states are required to take measures to ensure compliance with these standards by 2030[601]. The legislation also strengthens legal avenues for citizens, making it possible for people who suffer health damages from excessive air pollution to claim compensation when EU rules are violated. This aims to bring more clarity on access to justice, effective penalties, and better public information[602]. However, even with these revisions, the AAQD remains less stringent than the 2021 WHO Air Quality Guidelines[603], which set substantially lower thresholds for $PM_{2.5}$ and NO_2 in particular. For example, the WHO guideline for $PM_{2.5}$ is 5 µg/m³ annual mean, while the updated EU limit remains higher at 10 µg/m³. This means that even if EU countries achieve full compliance by 2030, Europeans will still face pollution levels above what the WHO considers safe for health.

For the first time, the revised AAQD also includes a monitoring requirement for ultrafine particles (UFPs, <0.1 µm). Although no binding limit values are set yet, this requirement is widely seen as a critical pre-step towards establishing enforceable UFP regulations[604]. The WHO has stated that concentrations above 20,000 particles per cm³ represent a high level of exposure[605]. Urban monitoring campaigns across Europe show that such levels are frequently exceeded near busy roads[606], airports[607], and ports[608]. Limited monitoring data around the Port of Rotterdam, combined with atmospheric modeling, indicate that UFP concentrations are elevated compared to regional background, with shipping identified as a major contributor[609]. However, systematic long-term monitoring is still limited[610], and Rotterdam's new Air Quality Program may help generate the data needed to align EU regulation with WHO health-based guidelines.

At the national scale, the Dutch government monitors air quality through the RIVM Air Quality Monitoring Tool and publishes annual reports[611]. Modelling by RIVM found that with existing policy measures, the air quality in 98% of the Netherlands will meet the updated EU requirements by 2030. However, exceedances are projected to persist for NO_2, especially near busy roads, in the IJmond and Maasvlakte regions, and around Amsterdam Airport Schiphol[612]. Along major roads, meeting the new NO_2 limits will require a further 10% reduction in traffic emissions by 2030.

The Clean Air Agreement (Schone Lucht Akkord, or SLA) is an agreement between the Dutch national government, provinces, and over 100 municipalities, with the goal of reducing health damage from air pollution by at least 50% by 2030 compared to 2016. All 12 provinces are signatories.

At the local level, the Municipality of Rotterdam is developing a new Air Quality Program under the Environment and Planning Act framework[613]. Based on simulations, the city does not expect to meet nitrogen dioxide NO_2 standards at several locations[614]. The city is pursuing a participatory process for the development, including residents surveys, street interviews, and in-depth group discussions with the key stakeholders[615]. The results of the process are expected in fall 2025, and a participation report will be published after the new municipal council has approved the draft program in 2026[616].

Rotterdam regulates road traffic emissions through two complementary systems: a zero-emission zone for commercial goods vehicles and a low-emission zone for passenger cars. The zero-emission zone currently applies to commercial vans and trucks transporting goods. Full enforcement began in July 2025[617]. It applies to commercial vehicles (vans and trucks) transporting goods. Only zero-emission vehicles, such as electric and hydrogen-powered vans and trucks, are permitted to enter. Older diesel and petrol goods vehicles are being gradually phased out through exemption rules, giving businesses time to adapt their fleets.

The low-emission zone (milieuzone) applies to passenger cars and diesel vans. Here, restrictions specifically target older diesel vehicles – those with emissions standard 4[618] may only enter designated green zones, while those with emissions standard 5 are permitted in blue zones[619]. Petrol or gasoline vehicles, electric vehicles, and hydrogen vehicles are allowed to enter all areas without restrictions. Only diesel vehicles face access limits, with older Euro 4 and Euro 5 diesel models restricted to specific zones.

Environmental factors like surface and air temperature, cloud cover, wind speed and direction, precipitation and relative humidity can strongly influence pollutant concentrations in certain regions[620]. A study on nitrogen pollution in Rotterdam found that normally higher wind speeds result in lower pollutant concentrations but this was not observed for the comparatively strong westerly winds. Additionally, wind direction is not distributed equally[621], making it difficult to predict pollution impacts.

Direct Impacts of Shipping and Ports: Drivers and Consequences

Ships predominantly use fossil fuels for propulsion and on-board electricity generation. Combustion of heavy fuel oil, marine gas oil, and other distillates emits a complex mix of air pollutants, including particulate matter (PM), sulphur oxides (SO_x), nitrogen oxides (NO_x), volatile organic compounds (VOCs)[622], and ultrafine particles (UFPs)[623]. Heavy fuel oil combustion generates significant emissions of sulphate aerosols and trace metals, particularly vanadium and nickel[624]. UFPs, which penetrate deep into the lungs and can enter the bloodstream[625], are a major health concern. Shipping remains a significant source of UFPs, the primary source of UFPs in Europe[626], raising concerns about health impacts in port cities[627]. Yet systematic monitoring of UFPs in port cities remains limited[628], and further research is needed to better understand their contribution to health damage.

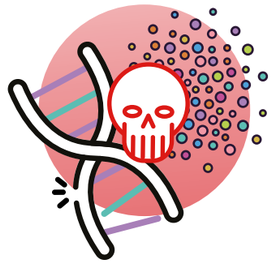
Maritime contribution to the overall $PM_{2.5}$ emissions from the EU-27 transport sectors has increased slightly over time, reaching approximately a 43% of total transport-related $PM_{2.5}$ emissions in 2022[629]. Research found that ~84,800–103,000 premature deaths worldwide were linked to PM2.5 exposure from maritime shipping in 2015, with 83% of these deaths associated with international shipping activities and 17% with domestic shipping[630]. The regional contribution varies considerably: in China, 44% of shipping-related premature deaths in 2015 stemmed from domestic shipping air pollutants[631].

Annual mean concentrations of PM_{10} and NO_2 in 2021 were found to be higher in port areas than in surrounding regions. Black Carbon emissions from the maritime sector, expressed as a share of the EU transport sector's overall emissions, have also risen steadily, reaching about 17% in 2022[632].

Globally, emissions from oceangoing ships are estimated to represent 5–8% anthropogenic sulphur oxides (SO_x) and around 15% of anthropogenic nitrogen oxides (NO_x). Roughly 70% of shipping-related air pollutants are released within 400 km of coastlines, underscoring their impact on coastal cities such as Rotterdam[633].

Ship tracks, cloud streaks visible in satellite imagery[634], form when water vapor condenses around tiny particles of pollution that ships emit as exhaust or from gases in the exhaust[635]. They are especially common in regions with low-lying stratus and cumulus clouds. The number of ship tracks dropped significantly after the International Maritime Organization's 2020 sulphur regulation[636], which reduced the allowable sulphur content of marine fuels, thereby cutting sulphur air emissions from ships. COVID-19-related trade disruptions have also played a small role in the reduction[637].

A toxicological study found that when human cells were exposed to particles from a range of marine fuels (including heavy fuel oil, low-sulphur fuel oil, and marine gas oil), many cells died or could not reproduce properly[638]. More serious genetic damage, such as DNA breaks associated with cancer risk, was not primarily linked to sulphur content but to polycyclic aromatic hydrocarbons (PAHs), toxic chemicals that form when fuel burns incompletely[639]. Incomplete combustion is a common feature of ship engines[640], meaning PAH emissions are a widespread health risk in port regions.



A toxicological study found that when human cells were exposed to particles from a range of marine fuels, many cells died or could not reproduce properly

Black carbon (BC), or soot, is another major concern. It is a component of $PM_{2.5}$ and is strongly associated with UFP emissions. A recent ICCT study[641] estimated that globally BC accounted for 8% of the total Tank-to-Wake (TTW) CO_2e emissions between 2016 and 2023. Its health and climate impacts are thus disproportionately large relative to its share of emissions by mass.

Although cruise ships make up only a small fraction of the global merchant fleet[642], they have an outsized impact on local air quality. The massive onboard energy requirements for passenger services such as air conditioning, refrigeration, and entertainment produces high levels of emissions. Despite the 2020 sulphur cap, Europe's 218 cruise ships emitted as much sulphur oxides (SO_x) in 2022 as 1 billion cars[643]. For context, the EU had roughly **250 million registered passenger cars** in 2022, meaning that cruise ships' SO_x emissions outweighed those of the entire European passenger car fleet[644].

A comparative analysis of nearly 5,000 ports across 35 OECD countries (2001–2018) found that port regions pollute more than non-port regions, and that associated health impacts depend on the size and specialisation of the port[645]. The study differentiated between 3 types of port regions: industrial, intermediate, and metropolitan. Industrial port regions, those dominated by heavy industry and bulk cargo, were linked to higher premature mortality and lower life expectancy, while metropolitan port regions (characterised by high container traffic and population density) also showed elevated pollution levels due to the concentration of both port activities and urban populations. Understanding these dynamics is relevant for Rotterdam, which combines Europe's largest container port operations with significant petrochemical and heavy industrial activity.

Solutions and Maritime Interventions

Emission Control Areas (ECAs): ECAs are designated zones where stricter emission standards apply to reduce NO_x, SO_x, and particulate matter (PM) to improve public health. These areas are considered environmentally and socially sensitive regions because they often coincide with heavily populated coastlines, dense shipping lanes, or ecologically important seas. Control is achieved by limiting fuel sulphur content to 0.10% m/m, five times lower than the 0.50% m/m global sulphur cap[646], and depending on the ECA, enforcing Tier III NO_x standards for newer ships[647]. ECAs reduce human exposure to toxic air pollution, alleviate acidification pressures on terrestrial and freshwater ecosystems, and protect biodiversity in fragile marine habitats.

Currently, there are five ECAs[648]: the Baltic Sea, the North Sea, the North American area, the United States Caribbean Sea, and the Mediterranean Sea (SO_x ECA only[649]). Two more, the Canadian Arctic Waters and the Norwegian Sea, will come into force in 2026[650].

Heavy Fuel Oil (HFO) restrictions in the Arctic: Black carbon emissions and oil spills in the Arctic already do result in serious, long-lasting damage to vulnerable ecosystems. The region's cold climate, ice cover, and limited sunlight slow the natural breakdown of oil, meaning spills persist for decades and devastate marine life and coastal communities. To address this, a ban on the use and carriage of HFO as fuel came into force on 1 July 2024[651]. While a significant step forward, the regulation contains exemptions and waivers that postpone full implementation until 2029[652]. These loopholes mean that around 74% of Arctic shipping activity currently remains unaffected by the ban[653]. The cumulative effect is that the risk of HFO spills and associated black carbon emissions will continue at a large scale for most of this decade, undermining the immediate environmental benefits of the policy. The behaviour of the new fuel blends and biofuels under weather conditions in the Arctic is an active area of research[654].

Driven by receding ice and expanding mineral extraction, the number of unique ships operating in the Arctic increased by 37% between 2013 and 2023[655], intensifying both the urgency of spill risk management and the need for stricter black carbon controls.

IMO Sulphur Regulation: The IMO's global sulphur regulation came into force on 1 January 2020, reducing the upper limit of sulphur content in ship fuel oil from 3.5% to 0.5%[656]. Compliance options include using low-sulphur fuels such as VLSFO, ULSFO, marine gas oil (MGO), LNG, biofuels or other blends, or installing so-called *exhaust gas cleaning systems*[657] better known as scrubbers, which often simply transfer sulphur pollution from the air to the water.

Recently published data showed that SO_2 emissions from international shipping fell by about 8.4 Tg (or 8.4 million tonnes), dropping from 10.4 Tg in 2019 to 2.0 Tg in 2020. This aligns closely with the IMO's projected reduction of 8.5 Tg decrease from the introduction of the sulphur cap[658]. However, this also reduced the "sulphur mask" effect, where sulphate aerosols from shipping temporarily cooled the planet by reflecting sunlight. With fewer sulphates in the air, short-term radiative forcing increased by about +0.1 W/m² between 2020 and 2024[659] making shipping's underlying warming impact more visible. At first glance, this trade-off might seem counterproductive for climate goals. In reality, it is a climate win: the apparent cooling from sulphur pollution was never a sustainable strategy, and its removal strengthens incentives for genuine reductions in greenhouse gas emissions rather than reliance on the accidental side-effects of dirty fuels.

The fact that this change is detectable in the global atmosphere just four years after the policy entered into force demonstrates that maritime regulations can deliver measurable results within politically relevant timescales – while also highlighting that effective environmental policy often requires navigating nuanced trade-offs rather than looking for simplistic "win-win" scenarios.

IMO NO_x regulation: MARPOL Annex VI establishes a tiered regulatory framework for limiting nitrogen oxide (NO_x) emissions from marine diesel engines above 130 kW[660]. The three-tier system sets progressively stricter standards based on engine installation dates: Tier I and II limits apply globally, while the most stringent Tier III limits are enforced only in designated Emission Control Areas (ECAs)[661].

An ICCT study, based on data from helicopter-mounted sniffers sampling ship exhaust plumes, found that actual NO_x emission rates are often higher at low engine loads, since ships frequently operate at lower loads than those assumed in NO_x certification test cycles. In practice, this means that while ships are near the shore or in port, where they tend to operate at reduced speeds, they may emit disproportionately high levels of NO_x, amplifying air quality harm on nearby coastal communities[662]. The study concluded that the NO_x Technical Code should be updated to include test points at low engine loads and highlighted the need for stronger compliance monitoring in Tier III ECAs[663].

Energy efficiency technologies: Reducing fuel consumption through energy efficiency will lead to a direct reduction in emissions. As future fuels are expected to be more expensive than conventional fossil fuels, combining their use with efficiency measures reduces costs and strengthens the business case for their adoption[664]. Technologies include air lubrication systems, wind-assist devices, waste-heat recovery, and advanced hull coatings.

Operational measures: Changes in how ships are operated can deliver immediate benefits. These include slow steaming (sailing at lower speeds), just-in-time arrival (optimising voyage speed to reduce time waiting at berth), weather routing, timely hull and propeller cleaning, and appropriate crew training[665]. Such measures can reduce both emissions and fuel costs in the short term.

Shore power: Shore power (also known as cold ironing or onshore power supply) allows ships to switch off their auxiliary engines while at berth and draw electricity from the local grid to power onboard systems. This eliminates onsite emissions in port[666], improving air quality for workers and nearby residents. While the electricity supplied may still come from fossil-fuel-based generation, overall emissions are generally lower than from onboard auxiliary engines, and the climate benefit increases as national grids integrate more renewable energy.

Alternative fuels and batteries: Shifting away from fossil marine fuels can substantially cut particulate matter, but the benefits vary by fuel pathway and engine technology. **Combustion of biofuels and e-fuels (e.g., hydrogen – or CO_2-derived methanol, e-diesel, ammonia blends)** in internal-combustion engines can still generate **NO_x, PM**[667, 668]**,** UFP **and PAHs.** Lube-oil ash also contributes to particle emissions.

A recent study[669] with **ammonia** engines found that switching to NH_3–H_2 engines avoids 16,900 mortalities from $PM_{2.5}$ and 16,200 mortalities from ozone formation annually. The same analyses also show that pure NH_3 engines with significant unburnt NH_3 slip could lead to 668,100 $PM_{2.5}$ – related deaths annually under current legislation. The results from the study show that ammonia-powered ships, when running on ammonia generated via clean upstream electricity, could offer a more climate-friendly solution than fossil fuels by lowering CO_2 emissions and supporting IMO GHG targets. However, to avoid negative impacts of air pollutants on health and the environment, stringent new ammonia emission regulations would be needed, particularly for pure ammonia engines, or they would increase global deaths from $PM_{2.5}$[670]. Without stringent measures to limit NH_3 slip, NO_x formation, N_2O emissions, and related air pollutants (including likely UFP), the total CO_2e and health impacts could be worse than today's fuels.

Fuel cells: Fuel-cell pathways generally yield much lower aerosol pollution than combustion engines. Fuel cells operating on pure hydrogen produce no direct harmful emissions[671], emitting only water vapour. Fuel cells using ammonia directly can be designed to keep NO_x very low, depending on the fuel cell type and operating conditions[672]. Energy systems using hydrogen fuel cells with ammonia cracking require careful control of cracker emissions. All fuel cells using ammonia require careful monitoring and treatment of residual ammonia[673].

Batteries (hybridisation): Studies of battery systems in maritime applications show that lithium-ion batteries and supercapacitors are effective tools for reducing pollutant emissions by minimising diesel generator usage during port stopovers, resulting in a 55% reduction in carbon dioxide emissions during port stays[674].

Electrified port equipment: Electrification of shore-side port equipment like cranes, yard tractors, and terminal vehicles also offers significant environmental advantages by eliminating local emissions of nitrogen oxides, particulate matter, and other air pollutants from diesel-powered cargo handling equipment. Using low-carbon electricity to power port operations reduces the harmful impacts of port operations on those who live and work near ports and are impacted inequitably by air pollution and other environmental externalities of traditional port activities[675].

Monitor and set targets for port industrial clusters: Multi-pollutant emissions inventories can help port operators identify and quantify the relative contributions of different mobile and point source sectors[676]. Different port industrial clusters comprise different combinations of mobile sources (vessels, trucks, cargo handling equipment) and stationary facilities (factories and processing facilities). Assessing the air pollution data and enforcing strict controls on the major contributors will be key to improving air quality in ports.

Multi-pollutant emissions inventories can help port operators identify and quantify the relative contributions of different mobile and point source sectors.

Current Contributions and Facts from the Port of Rotterdam

The Port of Rotterdam is within the North Sea NO_x Emissions Control Area, which came into force in 2021[677]. Ships constructed on or after 1 January 2021 and operating in the North Sea ECA must comply with the Tier III NO_x standard, which requires approximately 80% reduction in NO_x emissions compared to Tier I levels[678].

The Human Environment and Transport Inspectorate (ILT)[679] is the primary Dutch authority responsible for enforcing MARPOL Annex VI NO_x regulations in Rotterdam port. The ILT ensures ships in or registered in the Netherlands are safe, sustainable, and comply with national rules and regulations.

The Municipality of Rotterdam and Port of Rotterdam Authority are working together on a joint rollout of shore-based power for sea-going vessels, aiming for a significant share of vessels to 'plug in' when moored by 2030 through a joint project called CABLE (Connecting All Berths for Lower Emissions)[680]. Currently, shore power is available at 10 berths in 7 locations in the port. 12 additional locations have been announced or are under construction and an additional 6 are being studied[681]. The Port Authority and Eneco established Rotterdam Shore Power as a company offering shore power as a service, developing, financing, realising and operating shore power for clients, to facilitate the deployment of shore power in the port[682].

Several energy and raw material transition projects[683, 684] are underway at the Port of Rotterdam, including, among others, expansion of the electricity grid, hydrogen and biofuels production, hydrogen pipelines, fuel certification, and ammonia production, cracking and bunkering.

Recommendations for the Port of Rotterdam

- **Shore power expansion and related incentives:**
  Continue to expand shore power infrastructure and create incentives for shipowners and operators to 'plug in' and share data on energy consumption in port. Incentives that can help secure long term offtake agreements will speed up the build out of shore power infrastructure. Incentives for data sharing will enable the port and terminals to plan for an appropriately designed infrastructure capacity and modality.

- **Enhance monitoring systems:**
  Install comprehensive aerosol monitoring networks throughout the port complex to establish baseline measurements and track progress. Include UFP/BC monitoring (at fenceline, quays, roads, Maas channel), and create dashboards to provide insights on trigger levels, source apportionment and annual overviews.

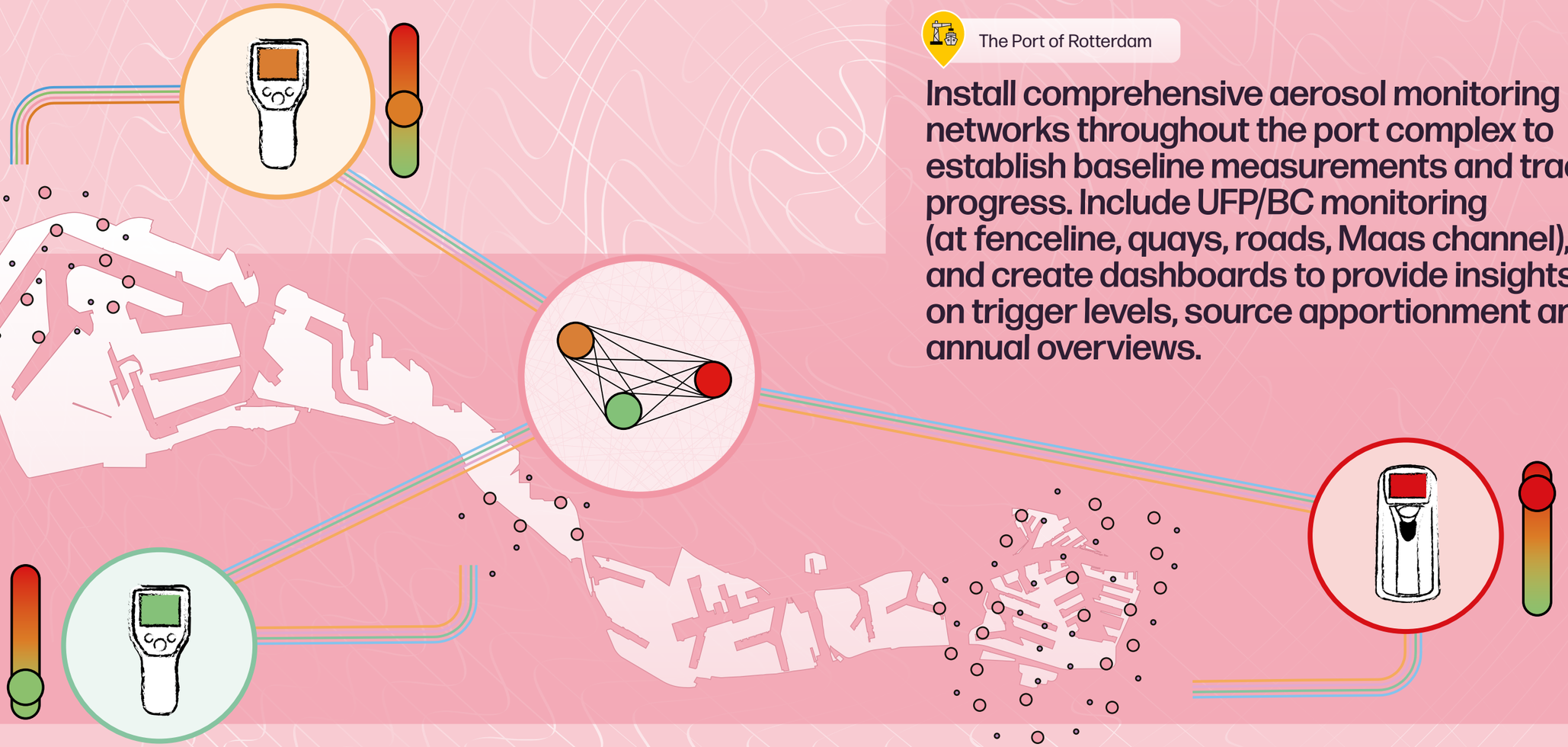
- **Expand on Digital Initiatives to improve efficiency of shipping activity:**
  Continuously deploy latest digital technologies to improve port operations, minimise vessel waiting times and optimise berthing schedules to reduce emissions. Explore tying berth priority to vessel emissions, recognising that aerosols may have an outsized local impact even when low in absolute quantities.

- **Extend Rotterdam's Zero-Emission Zones to shipping traffic:**
  Designate specific port areas as zero-emission zones, requiring all vessels to operate on clean fuels or electric power. Incentivise vessels to use these zones by offering financial or operational advantages like priority access. Phase out heavy fuel oil use at berth as a priority. Establish strict limits on ammonia slip, NO_x, and particulate emissions for any alternative fuels.

- **Expand Monitoring, Reporting, and Verification (MRV):**
  Require tenant facilities and visiting ships to report BC and particle number alongside CO_2e; integrate with AIS and meteorological data.

The Port of Rotterdam

Install comprehensive aerosol monitoring networks throughout the port complex to establish baseline measurements and track progress. Include UFP/BC monitoring (at fenceline, quays, roads, Maas channel), and create dashboards to provide insights on trigger levels, source apportionment and annual overviews.



Recommendations for Policymakers

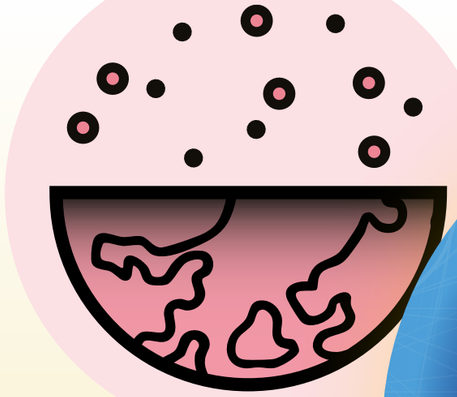
- **Expand regulatory coverage to aerosols:**
  Expand the Monitoring, Reporting, and Verification (MRV) and subsequently the EU Emissions Trading System to include black carbon and other aerosol precursors not adequately covered by current greenhouse gas or air quality regulations.
- **Foster innovation:**
  Create regulatory sandboxes, and public procurement requirements to accelerate aerosol reduction technologies from research to commercial deployment.
- **Create funding for aerosol research:**
  Significantly increase funding for atmospheric aerosol research, particularly focusing on maritime-climate interactions.
- **Consider maritime aerosols in planning:**
  Incorporate maritime aerosol considerations into public health planning, including air quality monitoring networks, health advisory systems, and emergency response protocols for acute pollution episodes.
- **Transform urban infrastructure into pollution sinks:**
  Invest in urban forest and green infrastructure projects to help filter particulate matter and mitigate aerosol impacts in port-adjacent neighbourhoods.
- **Collaborate with citizens and leverage their expertise:**
  Build on the collaborative process being employed for Rotterdam's updated Air Quality Program and create transparent communication channels to keep residents informed about air quality impacts and improvement efforts. Leverage expertise available in NGO networks and citizen science initiatives to create interventions that can have the most impact locally.

Conclusion and Call to Action

Though atmospheric aerosol loading is currently within safe operating limits, globally, it remains a critical planetary boundary with significant regional challenges and serious health risks, particularly in maritime environments. Air pollution, to which aerosols are a major contributor, is now the world's second leading risk factor for premature death, responsible for more than 8.1 million deaths (including both outdoor and household air pollution) in 2021[685].

The maritime sector contributes significantly to this burden, particularly in coastal regions and along major shipping routes. Complex aerosol interactions such as ship tracks altering cloud formation, fuel-dependent pollutant mixes, and regional weather feedbacks show that shipping can have disproportionately large local and climatic effects. After the IMO's 2020 sulphur regulation, the "sulphur mask" was lifted, making shipping's warming impact more visible and demonstrating both how quickly emissions interventions can reduce pollutant loads, and how nuanced climate outcomes can become.

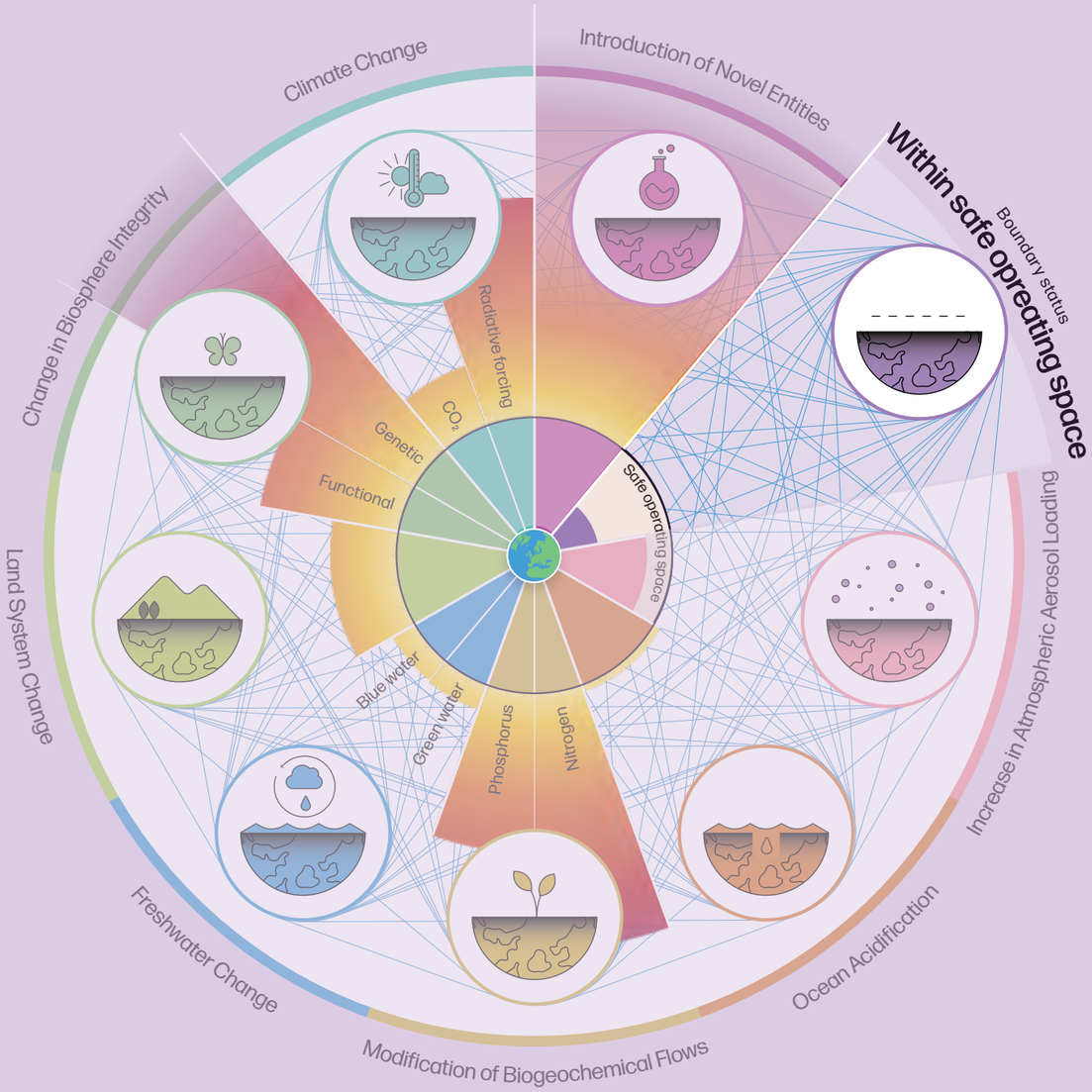
Effective aerosol pollution reductions must be proportional to the scale of the challenge, scientifically informed, economically viable, and socially equitable. Rotterdam's dual role as both Europe's largest port and a significant emissions contributor positions it as a critical proving ground for whether the maritime sector can successfully transition to sustainable operations while maintaining its vital economic function.



"Without air there can be no life, but breathing polluted air condemns us to a life of disease and early death."

United Nations Environment Programme (UNEP)

CH9 Stratospheric Ozone Depletion



CH2 Climate Change
CH3 Change in Biosphere Integrity
CH4 Land System Change
CH5 Freshwater Change
CH6 Modification of Biogeochemical Flows
CH7 Ocean Acidification
CH8 Increase in Atmospheric Aerosol Loading
CH9 Stratospheric Ozone Depletion
CH10 Introduction of Novel Entities

Figure 9.1 Planetary Health Check 2025 status: Stratospheric Ozone Depletion

Source. *Planetary Healthcheck 2025*. CC BY 4.0.

Introduction to the Boundary (Global)

Ozone (O_3) is a gas made up of three oxygen atoms. In the stratosphere, it forms a thin layer that protects life on Earth by absorbing harmful ultraviolet (UV) radiation from the Sun. Without this shield, humans, animals, and plants would be exposed to dangerous levels of UV.

Closer to the Earth's surface, in the troposphere, ozone plays a very different role. It is not emitted directly but forms as a secondary pollutant when nitrogen oxides (NO_x) from combustion processes (cars, trucks, planes, ships, power plants, and factories) react with volatile organic compounds (VOCs)[686] in the presence of sunlight. Major VOC sources include vehicle fuel vapors, paints, solvents, industrial emissions, and natural emissions from vegetation. This "bad" ozone is a key component of smog, toxic to humans, crops, and ecosystems.

Human-made chemicals such as chlorofluorocarbons or CFCs (e.g., refrigerants), halons (e.g., fire extinguishing agents), and other ozone-depleting substances (ODS) once used in refrigeration, air conditioning, fire suppression, and aerosols release chlorine and bromine when they break down in the stratosphere. Methyl bromide, mostly used as a fumigant, was a significant ODS whose phase-out has made the single largest contribution to ozone layer recovery[687]. These elements catalyse reactions that destroy ozone molecules, thinning the ozone layer and allowing more UV radiation to reach the surface.

The thickness of the ozone layer is measured in Dobson Units (DU)*. The pre-1980's baseline value for ozone concentration is **292 DU.** The planetary boundary is set at 277.4 DU, and in 2025 the global average was 285.7 DU, within the safe zone.

Put simply in a traffic light system, ~292 DU is "green," 2025's ~286 DU is "yellow but safe," and anything below ~277 DU would be "red," signaling a breached boundary.

When ozone concentration drops below 220 DU in polar regions, it is referred to as an 'ozone hole'. While the polar ozone hole is the most visible effect, ozone loss outside the polar regions (the extra-polar zone, 60°N–60°S) is more relevant for human health and ecosystems. The ozone hole phenomenon involves complex factors beyond just anthropogenic ozone-depleting substances (ODS), making extra-polar ozone a more relevant measure for a planetary boundary[688].

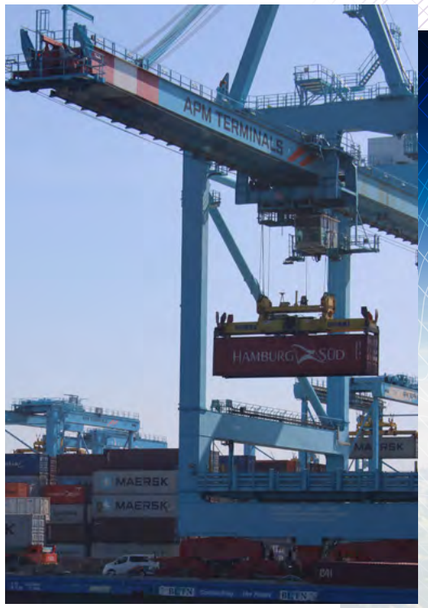
Ozone layer recovery represents one of humanity's most remarkable environmental and regulatory success stories. This reduction is a result of the Montreal Protocol, which has facilitated this phase out of 98% of controlled ozone depleting substances (ODS)[689†] globally compared to 1990 levels[690]. This figure excludes unregulated substances such as nitrous oxide (N_2O) and ODS used for exempted purposes (for example, CFCs and HCFCs employed as chemical feedstocks). The Montreal Protocol's success makes ozone recovery one of humanity's greatest environmental achievements through global collaboration. Scientists with NASA and the National Oceanic and Atmospheric Administration (NOAA) project the Antarctic ozone layer could fully recover by 2066[691].

* One DU represents a layer of ozone that would be 0.01 millimeters thick under standard temperature and pressure.

† An ODS is a substance that leads to stratospheric ozone depletion. Under the Montreal Protocol, most of the widely used ODSs are controlled under Annexes A, B, C, and E. These include, among others, chlorofluorocarbons (CFCs), carbon tetrachloride (CCl4), methyl chloroform (CH3CCl3), halons, methyl bromide (CH3Br) and hydrochlorofluorocarbons (HCFCs). These ODSs typically have sufficiently long atmospheric lifetimes to reach the stratosphere after being emitted at the surface. Methyl bromide is the shortest-lived of the controlled substances and has natural and anthropogenic sources. Other ODSs are not controlled under the Montreal Protocol. *https://csl.noaa.gov/assessments/ozone/2018/executivesummary/#section-5*

With CFCs being phased out, N_2O (which is not regulated by the Montreal Protocol) has now become the most highly emitted ozone-depleting substance[692]. Although it is listed under the Vienna Convention for the Protection of the Ozone Layer, it has received limited attention in countries' Nationally Determined Contributions (NDCs) under the UNFCCC[693, 694]. In the stratosphere, N_2O breaks down into reactive nitrogen oxides that catalyze ozone destruction. At the same time, it is a potent greenhouse gas, with a global warming potential nearly 300 times that of CO_2. This dual role makes N_2O both a climate and an ozone threat, underscoring the need for integrated strategies to address its emissions.

Ozone recovery is inherently slow due to the long atmospheric lifetime of ODS. While the ozone layer is recovering overall, recent research reveals complexities: mid-spring Antarctic ozone has continued declining since 2004, and global recovery may have plateaued in recent years[695]. Since 2006, the projected recovery date has been pushed back from 2049 to 2066 (over the Antarctic)[696] due to including changes in modeling assumptions, unanticipated emissions, and larger-than-expected sources of lawfully produced ozone-depleting substances (ODS) – some manufactured recently to be used as feedstock, others leaking from old equipment[697]. The slow nature of atmospheric recovery means that substances released today can continue affecting the ozone layer for decades, making prevention of any backsliding critical for maintaining this planetary boundary within safe operating space.



Failure to maintain momentum on ozone layer protection would trigger cascading environmental and health consequences:

- **Human health implications:** Without the Montreal Protocol, ozone depletion would have been 10 times worse by 2050 compared to current levels, leading to millions of additional cases of melanoma (a serious skin cancer that can spread to other organs), other cancers and eye cataracts (clouding of the eye's lens that causes blindness)[698]. In the US alone, full implementation of the Montreal Protocol is expected to prevent approximately 443 million cases of skin cancer, 2.3 million skin cancer deaths, and 63 million cataract cases among people born between 1890–2100[699]. However, recent assessments warn that without ambitious N_2O abatement, continued N_2O emissions could cause a 2–10% increase in skin cancer incidence (depending on latitude) and a 0.2–0.8% increase in cataract cases by 2080–2090 due to its contribution to stratospheric ozone loss resulting in increased UV exposure[700].

- **Ecosystem impacts:** Increased UV-B radiation (reaching the earth due to depleted ozone layer) damages phytoplankton (which forms the foundation of marine food webs) and reduces agricultural productivity[701]. For maritime ecosystems, this would mean fundamental disruption to food chains that support global fisheries and marine biodiversity. Excessive UV exposure also damages synthetic materials commonly used in shipping, including plastics, paints, and textiles, leading to accelerated degradation and increased maintenance costs[702].

- **Economic costs:** Healthcare costs from increased cancer rates, reduced agricultural productivity, and damage to UV-vulnerable materials would impose enormous costs on society.

The stratospheric ozone depletion boundary is connected to other planetary boundaries:

Climate Change: Most ozone depleting substances (ODS) are potent greenhouse gases. From 1990 to 2010, the Montreal Protocol is estimated to have reduced greenhouse gas emissions by the equivalent of 135 gigatons of CO_2[703]. Beyond its direct mitigation of these emissions, the treaty has also indirectly protected the Earth's carbon balance: enhanced UV exposure diminishes the capacity of the terrestrial carbon sink, and without the Montreal Protocol, plants and soils would be expected to store 325–690 billion tonnes less carbon by the end of the century. This would have led to an additional 0.85°C of warming on top of an estimated 1.7°C direct warming from CFC emissions, meaning the treaty has collectively avoided roughly 2.5°C of global warming through both greenhouse gas reduction and the preservation of the terrestrial carbon sink[704].

Novel Entities: Most ODS are synthetic chemicals that fall under the novel entities boundary. The Kigali Amendment to the Montreal Protocol requires a phasedown of high global warming potential HFCs (hydrofluorocarbons)* by more than 80% (in CO_2-equivalent) over the next 30 years. This is expected to avoid up to 0.4°C of global warming by the end of the century[705]. Ocean processes, biomass burning and soil emissions may naturally emit methyl bromide, methyl chloride and nitrous oxide which contribute to ozone depletion. Though natural sources provide a significant baseline contribution, particularly for substances like N_2O and methyl bromide, synthetic ODS have been the primary drivers of ozone depletion[706, 707].

Increase in Atmospheric Aerosol Loading: Several aerosol products such as hairspray, antiperspirant, and spray paint historically contained ODS as propellants[708]. These uses have now been phased out and replaced by other compounds.

* CFCs were originally the main target. HFCs which are not ozone-depleting, but have a high global warming potential, were included in scope via the Kigali Agreement.

National Context: The Netherlands

The Netherlands is party to the Montreal Protocol and all its amendments, including the 2016 Kigali Amendment addressing HFCs[709]. As an EU member state, the Netherlands implements the new EU Regulation (2024/590) on ozone-depleting substances, which introduces stricter measures than Montreal Protocol requirements. The Dutch national monitoring programme includes continuous measurement of UV radiation levels through RIVM (National Institute for Public Health and the Environment), which calculates daily UV index values and provides public health guidance[710].

The Netherlands' intensive agricultural system presents challenges for managing N_2O, now the dominant anthropogenic ODS, given the country's characteristically high nitrogen inputs from both synthetic fertiliser and manure[711]. Studies have found that indirect N_2O emissions in the Netherlands are at least ~20% higher because more specific emission factors can be applied that are higher than the IPCC default, suggesting that indirect N_2O emission due to deposition is underestimated in current N_2O budgets[712].

Direct Impacts of Shipping and Ports: Drivers and Consequences

The maritime sector faces unique challenges in phasing out ozone-depleting substances (ODS) due to operational requirements and regulatory complexity. Vessels require refrigeration, air conditioning, and fire suppression systems that have historically relied on ODS[713, 714]. Because ships operate globally across multiple jurisdictions with varying levels of Montreal Protocol enforcement, consistent accounting and compliance remain difficult[715].

Ports host reefer facilities, short for *refrigerated container facilities*, industries and industrial plants that require extensive refrigeration or air conditioning, e.g., for perishable goods, pharmaceuticals, and chemicals. Storage areas may also temporarily hold substances containing or releasing ODS.

Beyond ODS, maritime and port activities can indirectly affect ozone levels through emissions of nitrous oxide (N_2O). Combustion processes release N_2O from ship engines and port equipment, while ammonia cracking[716] and fertilizer handling at ports add further risk. As ammonia (NH_3) is increasingly promoted as a hydrogen carrier and as a potential low-carbon marine fuel; lifecycle assessments must account for its direct and indirect N_2O emissions, which contribute to climate change and also deplete stratospheric ozone.

Globally, industrial and energy-sector N_2O emissions make up about 14% of human-caused totals, equal to roughly 372 $MtCO_2$-eq annually. Yet existing low-cost abatement technologies, already widely deployed in some regions, could reduce these emissions almost entirely to zero[717] if fully implemented.

Solutions and Maritime Interventions

The Montreal Protocol: The Montreal Protocol on Substances that Deplete the Ozone Layer is the landmark multilateral environmental agreement regulating the production and consumption of nearly 100 human-made chemicals. Adopted in 1987, and achieving universal ratification by 2009 (197 states plus the European Union), the treaty phases out the production and consumption (rather than the direct emission) of ODS in a stepwise manner with binding, time-bound targets for both developed and developing countries. Under this treaty, all parties have specific responsibilities related to the phase out of the different groups of ODS, control of ODS trade, annual reporting of data, national licensing systems to control ODS imports and exports, and other matters. Developing and developed countries have equal but differentiated responsibilities, but most importantly, both groups of countries have binding, time-targeted, and measurable commitments[718]. Importantly, the countries are supported in implementing the necessary measures to meet their compliance obligations by the Multilateral Fund. This fund acts as a grant giving body, and is likely one of the most significant reasons for the treaty's success, contrasted with the underfunding that has hindered many subsequent international environmental agreements. Globally, the Parties to the Montreal Protocol has already eliminated about 98% of controlled ODS compared to 1990 levels[719]. Building on this success, the 2016 Kigali Amendment expanded the Protocol's scope to include hydrofluorocarbons (HFCs), potent greenhouse gases that, while not ozone-depleting, pose severe climate risks. As of today, over 160 countries have ratified the amendment, reinforcing the Protocol's dual role in protecting both the ozone layer and the global climate[720*].

EU Ozone Regulation: To fulfill its obligations, the EU has gone further than the Montreal Protocol[721] through the EU Ozone Regulation[722†] one of the strictest and advanced regimes in the world. Through a series of regulations, the EU has not only implemented the Montreal Protocol but has often phased out dangerous substances faster than required. The Ozone Regulation also encompasses five additional ODS that are not covered by the Montreal Protocol and sets licensing requirements for all exports and imports of ozone-depleting substances[723].

EU F-Gas Regulation[724]: This regulation addresses fluorinated greenhouse gases for climate protection, complementing the EU Ozone Regulation, to create a comprehensive framework for controlling harmful atmospheric substances. The F-gas Regulation includes an ambitious phase-down of HFCs that began in 2015, before the Kigali Amendment was even adopted, and aims to achieve a complete phase-out by 2050, with few exceptions for specific sectors. This regulation covers HFCs contained in products and equipment, not just bulk substances, and includes prohibitions on placing certain fluorinated gas-containing products on the market along with measures to prevent emissions[725]. Since HFC reduction obligations under the Kigali Amendment started to apply in 2019, the EU has consistently stayed well below its yearly target, e.g., 55% below in 2023[726].

This dual regulatory approach, addressing ozone impacts via the Ozone Regulation and climate impacts via the F-Gas Regulation, creates more stringent requirements than international minimums, contributing to the EU's strong performance in exceeding Kigali Amendment targets. It illustrates how complementary rules can be used to tackle substances that affect multiple planetary boundaries simultaneously. Such an integrated approach could be applied more broadly to products and services that put pressure on climate, biodiversity, air quality, and novel entities boundaries at the same time.

* The Montreal Protocol achieved universal ratification in September 2009. *https://ozone.unep.org/all-ratifications*

† Regulation (EU) 2024/590, which replaced the previous Regulation (EC) No 1005/2009 in 2024. *http://data.europa.eu/eli/reg/2024/590/oj*

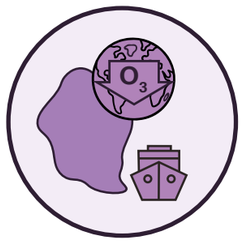
Technological solutions: A range of material and chemical innovations can help reduce or replace the use of ODS, including low-global warming potential (GWP) refrigerants, hydrocarbon and CO_2-based cooling, and non-ODS fire suppression systems such as water mist or inert gases. Abatement of N_2O emissions from transport, industrial and wastewater processes, which are co-benefits of decarbonisation and other environmental safety practices, can also contribute to protecting the stratospheric ozone layer[727].

ODS leak detection: Maritime ODS and fluorinated gases are estimated to amount to approximately 18.2 $MtCO_2$-eq annually, about 15% of total EU F-gas emissions[728]. A major driver is high leakage from ship cooling systems, with research showing average leak rates of ~40%, several times higher than stationary systems. Contributing factors include long piping, exposure to sea vibrations, and limited crew expertise, which can inhibit leakage repairs[729].

Enhanced monitoring and control: Improving cargo handling procedures to minimise emissions from onboard installations using ODS is important. Refrigeration technology is heterogenous across the fleet, reflecting diverse needs. For example, passenger cruise ships can use 7,000–8,000kg of refrigerant for the storage and provision of food, fishing vessels up to 1,500kg to preserve fish catch, and general cargo ships will use up to 150kg, mainly for air conditioning purposes. Reefers can use up to 6kg of a mixture of refrigerants (per container) to prevent spoilage of the load – **on large container vessels with 1,000–2,500 reefer slots, this translates to 6,000–15,000kg of refrigerant per voyage.** Technical data on the actual leakage rates of refrigeration and air-conditioning systems on ships is usually not available[730].

Improving crew training: Limited onboard expertise poses challenges that are characteristic for the maritime sector, especially in case of maintenance and repair needs during extended voyages. Training programmes for marine refrigeration technicians that include proper refrigerant handling and recovery techniques can help with reducing losses of ODS from onboard applications.

ODS disposal and recovery: Implementing proper waste management and recycling practices of ODS used on board vessels, especially at the time of dismantling ships, and providing ODS destruction facilities at major ports can also help reduce ODS related emissions from shipping. Such facilities should also employ destruction technologies approved by the Montreal Protocol's Technology and Economic Assessment Panel (TEAP)[731], which provides guidance on safe and effective methods for eliminating ODS[732] while minimising environmental impacts.

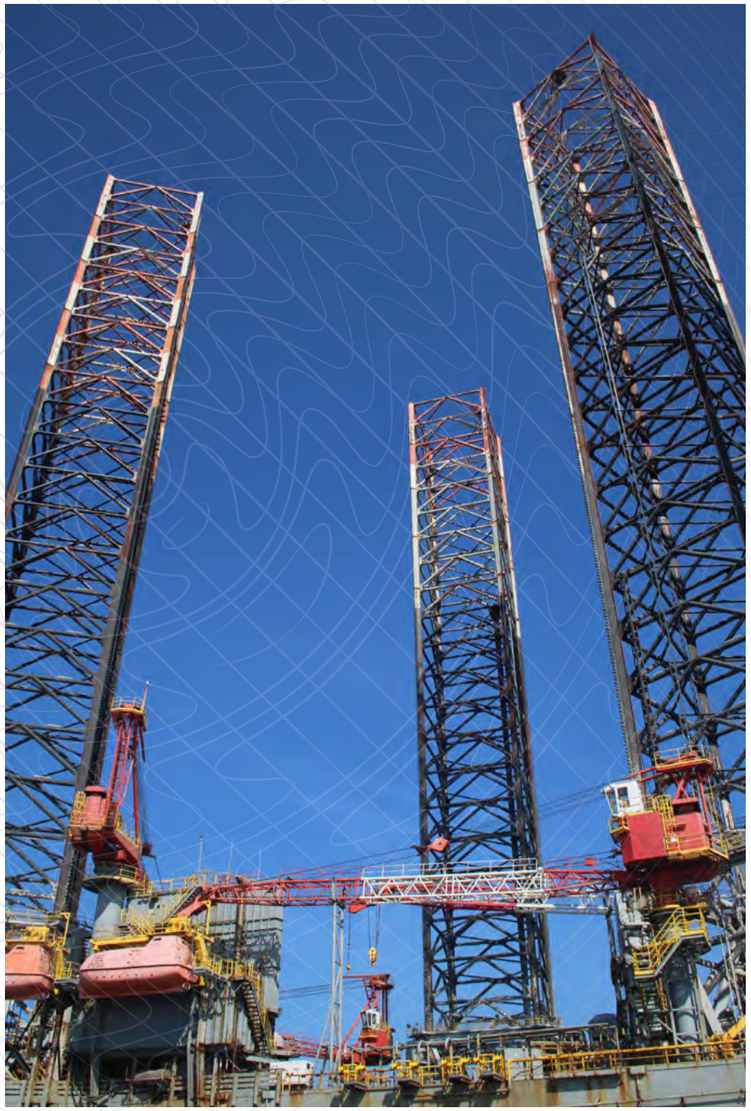


High leakage rates from shipboard cooling systems are a major source of ozone-depleting substances. Research indicates average leak rates of approximately 40%—several times higher than those of stationary systems. These elevated losses are driven by factors such as extensive piping, continuous exposure to vibration and harsh marine conditions, and limited crew expertise, all of which can hinder timely detection and repair of leaks.

Current Contributions and Facts from the Port of Rotterdam

Vessels arrive at the Port of Rotterdam from jurisdictions with varying regulatory frameworks. This creates both enforcement challenges and opportunities for Rotterdam to demonstrate leadership in sustainable maritime practices. Port State Control inspections verify compliance with International Air Pollution Prevention (IAPP) certificates, which must document ODS-containing systems and their proper management[733]. The port also enforces MARPOL Annex VI Regulation 12, which prohibits installation of ODS-containing equipment on ships constructed after specific dates: CFCs and halons after 19 May 2005, and HCFCs after 1 January 2020[734]. Illegal trade in in refrigerants is also a significant issue, with large seizures having been reported in Rotterdam[735].

Like several large ports, Rotterdam's infrastructure includes extensive cold storage facilities, container terminals, and ship servicing capabilities which rely on refrigeration systems.



Recommendations for the Port of Rotterdam

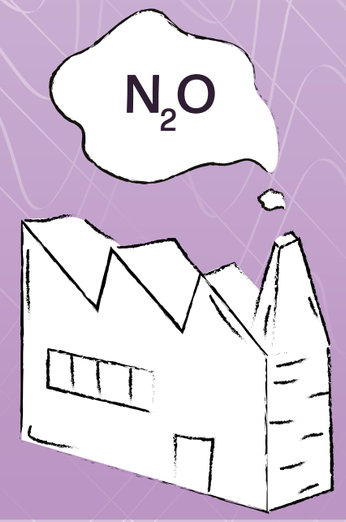
- **Establish comprehensive ODS monitoring and reporting systems:**
  Implement comprehensive systems for monitoring and reporting ozone-depleting substances across all port operations.
- **Require public disclosure of ODS handling and treatment:**
  Mandate public reporting of the quantities of ODS handled, collected and disposed of through port operations by requiring collectors and processing facilities to document and disclose their treatment and disposal methods.
- **Strengthen port state control for ODS compliance:**
  Enhance port state control procedures for verifying compliance with ODS regulations, including the adoption of standardised inspection protocols.
- **Implement digital tracking for ODS-containing equipment:**
  Introduce digital tracking systems for ODS-containing equipment throughout the port area, aligned with the port's ongoing digital transformation.
- **Develop guidance for vessel operators on ODS phase-out:**
  Provide vessel operators with clear guidance on ODS phase-out requirements and the alternative technologies available.
- **Create dedicated facilities for ODS disposal and recycling:**
  Establish dedicated reception facilities for the disposal and recycling of ODS-containing equipment.
- **Require N_2O monitoring and reduction targets for port industry:**
  Require port-area industries to monitor N_2O emissions and adopt reduction targets, prioritising electrification of equipment and deployment of abatement technologies where applicable.
- **Integrate ODS considerations into environmental ship index incentives:**
  Incorporate ODS, including N_2O, into the port's Environmental Ship Index[736] scoring or provide alternative incentives for environmentally friendly technologies that do not rely on ODS.
- **Establish N_2O standards for future ammonia-related operations:**
  Set N_2O emission standards for future ammonia-related port activities, including bunkering facilities and engine testing, with requirements for monitoring and mitigation technologies.
- **Support pilots for low-GWP refrigerants and alternative cooling technologies:**
  Support pilot projects demonstrating next-generation low-GWP refrigerants and alternative cooling technologies for maritime applications, including clean-fuel trials with integrated emissions monitoring.
- **Develop training programmes on ODS identification and handling:**
  Provide training programmes for port and vessel personnel on the identification and safe handling of ODS.
- **Establish a Best Practice Network with european ports:**
  Create a best-practice sharing network with other major European ports.

Recommendations for Policymakers

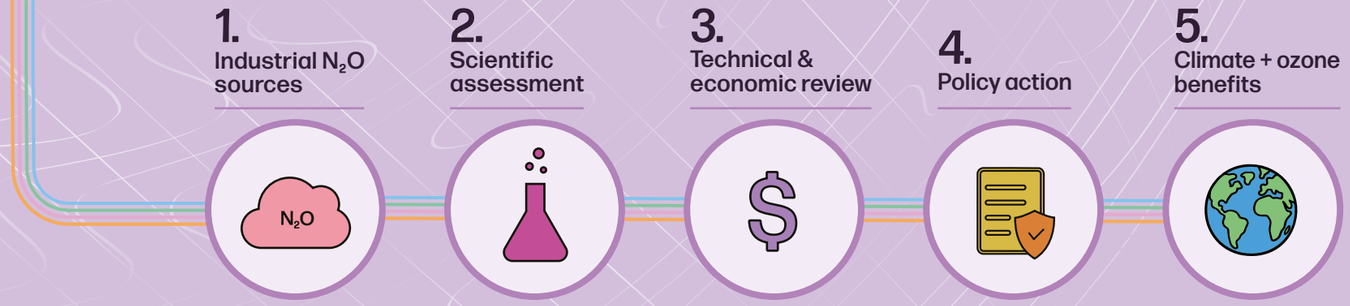
- **Support international action on industrial N_2O under the Montreal Protocol:**
  Endorse the Environmental Investigation Agency's recommendations for addressing industrial N_2O emissions under the Montreal Protocol. The Dutch government should request the Ozone Secretariat to engage with relevant stakeholders on controlling industrial N_2O emissions, including the Nitric Acid Climate Action Group (NACAG), the Climate and Clean Air Coalition (CCAC), the International Nitrogen Initiative (INI), the UNEP Nitrogen Working Group, and interested Parties. Call on the Technology and Economic Assessment Panel (TEAP), in coordination with the Scientific Assessment Panel (SAP), to produce a report on the technical feasibility, economic costs, and ozone and climate benefits associated with abating N_2O emissions from nitric acid, adipic acid, and caprolactam production. Request the SAP to produce a targeted report on the ozone and climate impacts of N_2O emissions from all sources and to outline projected trends for such emissions[737].

  Numerous studies have shown that the potential for high N_2O emissions associated with the use of ammonia as a fuel would offset its carbon-free advantages without appropriate abatement practices in place. Waiting until this technology is already deployed at scale before implementing clear regulations requiring the use of abatement equipment, much of which is still under development, will result in millions of CO_2-equivalent tonnes in unnecessary and avoidable emissions[738].

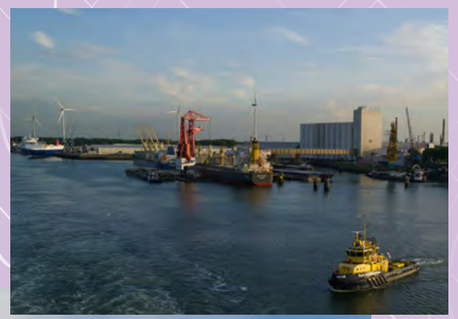
Global issue

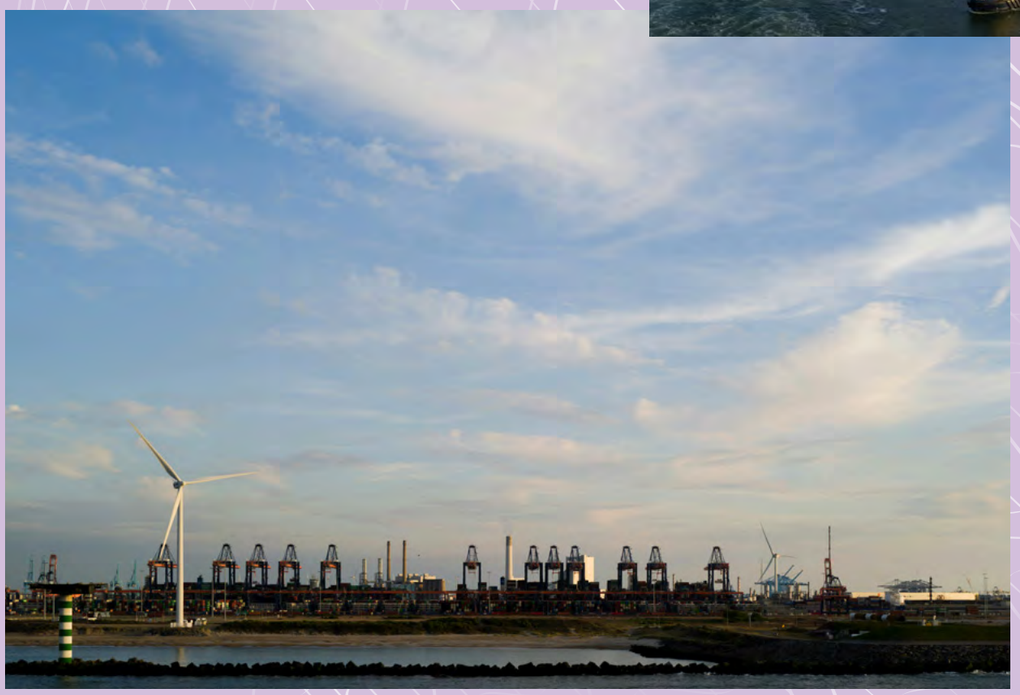


The Dutch government should request the SAP to produce a targeted report on the ozone and climate impacts of N_2O emissions from all sources and to outline projected trends for such emissions.



- **Financial incentives for early adoption of next-gen sustainable refrigerants:**
  Develop financial incentives that support early uptake of next-generation sustainable refrigerants.
- **Provide national funding for ODS alternatives research:**
  Allocate national funding to support research and development of alternatives to ozone-depleting substances.
- **Enhance transparency on national ODS use and compliance:**
  Improve transparency on national ODS use by sector to identify innovation opportunities and enable targeted action. Provide publicly accessible data on compliance rates, inspection frequencies, and penalty structures for ODS violations.





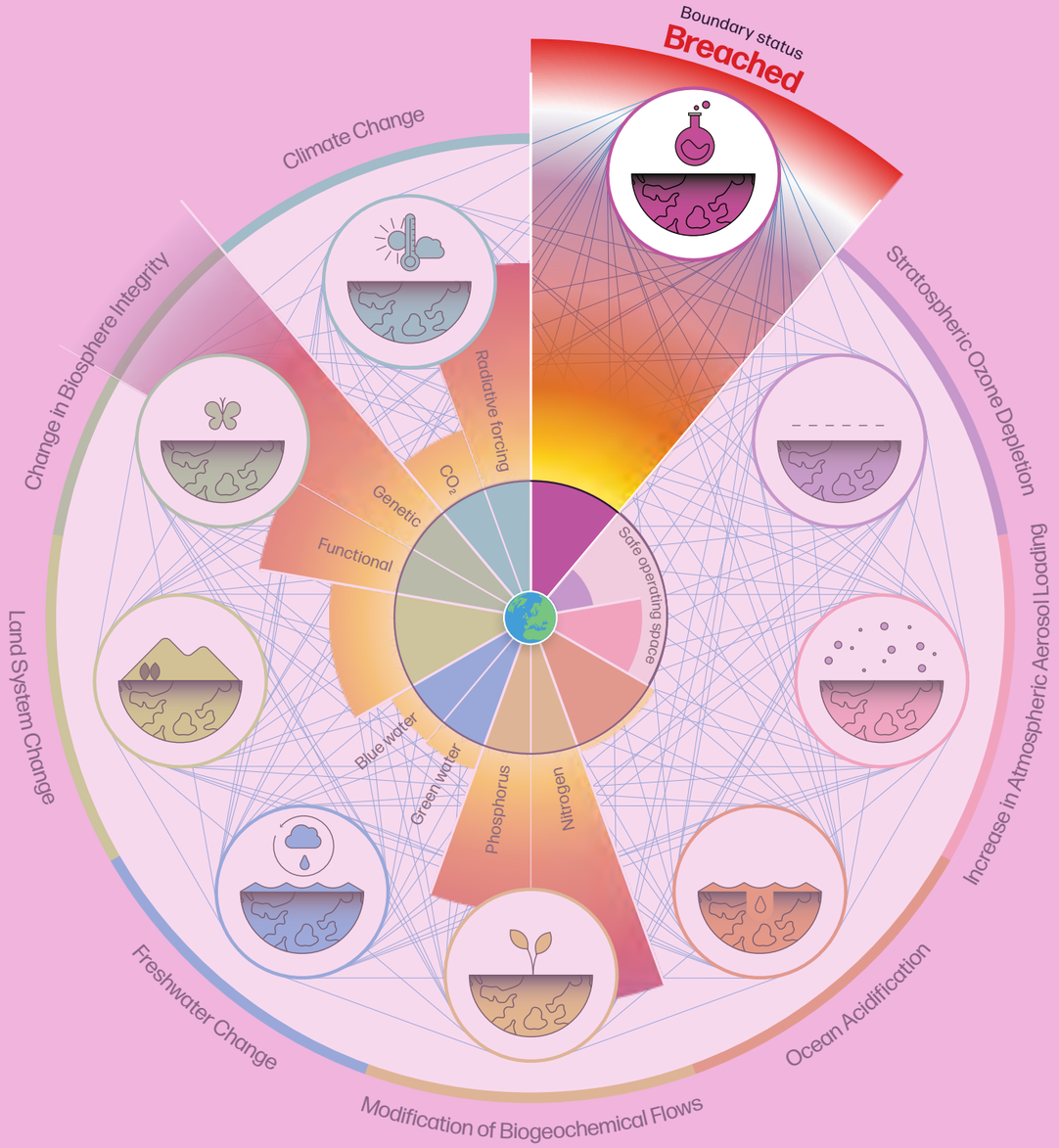
Conclusion and Call to Action

The ozone depletion planetary boundary stands as both a landmark environmental success and a reminder of the need for sustained vigilance.

Continued leadership by Rotterdam and the Netherlands, within the EU and on the global stage, will be essential to safeguard this achievement. Given the maritime sector's international reach, ports such as Rotterdam play a pivotal role as enforcement points and demonstration hubs for phasing out ozone-depleting substances. By embedding ozone protection into broader sustainability strategies, including climate action, energy transition, and circular economy initiatives, Rotterdam can address multiple planetary challenges at once, reinforcing its position as a frontrunner in sustainable port governance.

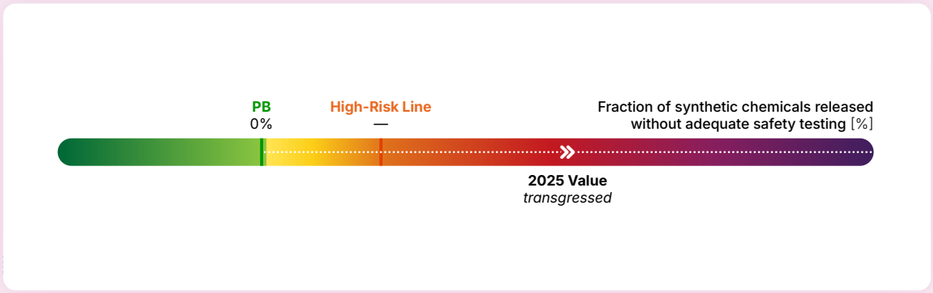
"The Vienna Convention and its Montreal Protocol became a landmark of multilateral success. Today, the ozone layer is healing"
UN Secretary-General António Guterres, in a message for World Ozone Day 2025.

CH10 Introduction of Novel Entities



CH2 Climate Change
CH3 Change in Biosphere Integrity
CH4 Land System Change
CH5 Freshwater Change
CH6 Modification of Biogeochemical Flows
CH7 Ocean Acidification
CH8 Increase in Atmospheric Aerosol Loading
CH9 Stratospheric Ozone Depletion
CH10 Introduction of Novel Entities

Figure 10.1 Planetary Health Check 2025 status: Introduction of Novel Entities



Source. *Planetary Healthcheck 2025*. CC BY 4.0.

Introduction to the Boundary (Global)

Originally termed "chemical pollution," this boundary was later renamed to "novel entities". Novel entities are intentionally or unintentionally manufactured chemicals, engineered materials, and their transformation products that have the potential to disrupt vital Earth system processes. This broad definition encompasses synthetic chemicals (e.g., pesticides, antibiotics, and industrial solvents), plastics, microplastics, nanomaterials, radioactive materials, genetically modified organisms, and other human-created substances that can disrupt the planet's self-regulating capacity[739].

Human-produced materials already cause biodiversity loss and contaminate precious habitats on land, freshwater, and in the ocean. The release of these substances into the environment at ever-increasing scales threatens the continued functioning of the Earth system, often in ways that cannot be anticipated until harmful effects have already occurred.

Microplastics have now been found in human blood streams, all regions of the lungs[740], placental tissues[741], in breast milk[742], in the testis and semen[743], and at the bottom of the ocean. Forever chemicals (PFAS) have been found not only in food, drinking water, and consumer products such as clothing[744], but also in wildlife[745] worldwide and in virtually all humans tested[746, 747, 748].

Global markets currently trade around 350,000 different types of manufactured chemicals or "novel entities," including pesticides, pharmaceuticals, plastics, and industrial chemicals[749]. Humans have invented more than 140,000 synthetic chemicals and produce vast quantities of approximately 2.3 billion tonnes annually, yet only a few thousand have been tested for their toxicity to humans or other organisms[750]. The movement of these substances is made possible primarily by maritime shipping, which acts as the backbone of global trade, transporting fuels, plastics, chemical feedstocks, hazardous intermediates, and wastes across regions and supply chains. These substances move through global supply chains, with ports and shipping playing key enabling roles.

While no single threshold exists for individual substances, this planetary boundary tracks broad indicators such as production and release rates of the different chemicals, the proportion of these substances entering markets without adequate safety assessment, and whether the rate of new chemical introduction exceeds society's capacity to evaluate their risks. These factors, per individual substance, are extremely difficult to monitor comprehensively. Proxies such as the EU REACH[751] database reveal that most substances are not being tracked, and still lack adequate safety data. Current evidence shows that the global scale of chemical production and emissions is far outpacing our ability to ensure safety, reflecting a clear transgression of the novel entities boundary.

To put this in context: worldwide chemical production has increased approximately 5,000% since 1950 and is projected to triple again by 2050 compared to 2010 levels, making the chemical industry the world's second-largest manufacturing sector[752]. Global plastic production alone increased by 79% between 2000 and 2015[753], with no signs of slowing.

If left unaddressed, breaching the Novel Entities boundary will have far reaching implications:

- **Cocktail effects and synergistic impacts:** One of the greatest uncertainties is how the vast "cocktail" of novel entities interacts within organisms and ecosystems. Chemicals can combine to produce additive or even multiplicative effects that are rarely captured in conventional safety studies, which typically assess toxicity in isolation[754].

- **Unknown human health impacts:** Microplastics from common packaging materials such as PET and polystyrene have now been detected in breast milk[755], baby feces, placentas[756] and human blood[757]. Laboratory studies suggest these particles may affect red blood cells in humans and potentially interfere with oxygen transport[758]. Studies in mice also show that nanoplastics can cross the blood-brain barrier and cause neurological effects[759]. The full extent of their health consequences for humans is only beginning to be understood.

- **PFAS in human blood:** In the Netherlands, virtually everyone carries measurable levels of PFAS. A study by the National Institute for Public Health and the Environment (RIVM) analyzing 1,500 blood samples found at least seven different PFAS compounds (including PFOA, PFNA, PFDA, PFUnDA, PFHxS, PFHpS, and PFOS) in almost all individuals. While PFOS was banned in 2008 and PFOA in 2020, the industry has replaced these with other compounds from the same chemical family. These "replacement PFAS" share the persistence and environmental mobility of the compounds they replaced, perpetuating the pollution problem despite targeted restrictions. To prevent "regrettable substitution", the Netherlands and several partner countries have proposed a comprehensive European ban on all PFAS. This proposal is currently under review by European scientific committees[760].

- **Destabilising other planetary boundaries:** The consequences of exceeding the Novel Entities boundary extend far beyond direct chemical toxicity, threatening the fundamental stability of Earth's life-support systems. They destabilise other planetary boundaries, including:

Biosphere integrity: Pesticides are toxic to plants and animals, causing death, genetic and physiological deformities and reduced growth. Alongside other chemicals such as industrial pollutants, mercury and heavy metals, these substances can disrupt the balance of ecosystems, with cascading effects on the ways in which the entire structure functions[761]. Some types of persistent chemicals get magnified in marine food webs, and studies have shown that despite regulations and mitigation measures, they continue to affect larger marine mammals like whales[762]. These same processes expose humans through consumption of contaminated fish and shellfish, meaning that toxic burdens move up the food chain into human diets as well.

Freshwater Change: Chemical pollution is pervasive in freshwater systems worldwide. Even remote regions such as the Arctic now host highly contaminated waters, as persistent compounds are transported long distances through atmospheric and oceanic currents[763], demonstrating the truly planetary scale of this boundary transgression[764]. Pharmaceutical waste represents a growing component of novel entity pollution, with over 900 different pharmaceuticals[765] detected in aquatic environments[766] worldwide, largely because conventional wastewater treatment systems cannot effectively remove these compounds before they enter water bodies[767].

Climate Change: Plastics alone generated an estimated 1.8 billion tonnes of greenhouse gases in 2019, representing 3.4% of global emissions[768]. The chemical sector as a whole is the world's largest industrial energy consumer and the third-largest source of direct CO_2 emissions. Roughly half of its energy input is not for fuel but as feedstock for products such as plastics and key base chemicals (ethylene, propylene, benzene, toluene, mixed xylenes, ammonia, methanol)[769]. The relentless growth in demand for these products locks the sector ever deeper into dependence on fossil-based greenhouse gas emissions, directly linking novel entities to the climate boundary.

The chemical sector as a whole is the world's largest industrial energy consumer and the third-largest source of direct CO_2 emissions.

National Context: The Netherlands

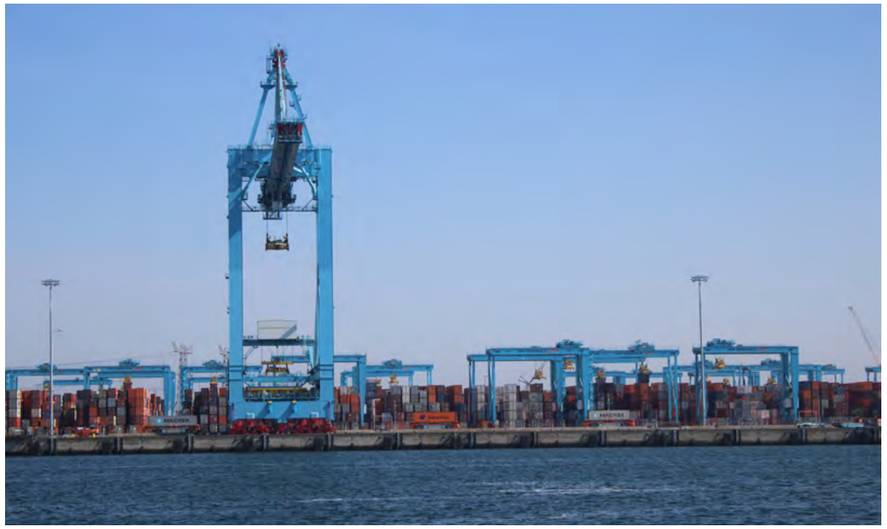
The Netherlands, along with France, Czech Republic, and Ireland, has called for a European policy package on sustainable carbon in the chemical industry. The aim is to accelerate the transition from fossil to sustainable raw materials, positioning the Dutch and wider European chemical industry as a global leader in green chemistry while safeguarding competitiveness[770].

The Netherlands has adopted and enforces the EU REACH regulation requiring manufacturers and importers to gather hazard information and assess risks for chemical substances before they are placed on the market.

The EU Marine Strategy Framework Directive (MSFD) and the Oslo Paris convention (OSPAR) both require monitoring and data reporting of microplastic particles in Dutch marine sediments. A 2024 study by Rijkswaterstaat analyzing Dutch marine sediments found that the most prevalent polymers were: polypropylene (59%), polyethylene (24%) together comprised 83% of microplastic polymers, with the remaining 17% consisting of polystyrene (11%), polyvinylchloride (2%) and "Other" polymers (4%)[771][772]. This polypropylene/polyethylene co-dominance aligns with patterns observed in other estuarine sediments globally. These dominant polymers reflect their widespread use in packaging, consumer goods, and construction materials:

- **Polypropylene (59%)** – commonly used in food packaging, textiles, ropes, and fishing gear, making it a major contributor from both land-based waste and maritime activities.
- **Polyethylene (24%)** – the most produced plastic globally, used for plastic bags, bottles, and films, much of which enters waterways through littering and poor waste management.
- **Polystyrene (11%)** – widely used for disposable food containers and insulation materials, prone to fragmenting into small particles.
- **Polyvinyl chloride (PVC, 2%)** – used in pipes, flooring, and building materials; its presence in sediments reflects losses from construction and demolition waste streams.

The dominance of these four polymer types illustrates how everyday plastic applications directly translate into long-term marine contamination, with consequences for Dutch coastal and marine ecosystems. Given Rotterdam's position as Europe's largest port, the Netherlands sits at a critical junction in the movement of novel entities, where upstream production and downstream consumption converge.



Direct Impacts of Shipping and Ports: Drivers and Consequences

Most fossil feedstocks, plastics, chemical intermediates, and hazardous wastes travel by sea. Control the maritime flows, and you control the majority of novel-entity movement. Ports are leverage points where standards, monitoring, and market access conditions can curb global circulation, fast. The maritime sector contributes to the transgression of the Novel Entities boundary both through its own operational discharges and as the principal logistics network that moves novel entities worldwide:

- **Ports are hubs for novel entities:** Ports act as hubs for pollutants released from ships and associated industries. For example, *biofouling*, the accumulation of algae, barnacles, and other organisms on ship hulls, requires cleaning and treatment with toxic paints and chemicals. Over time, port *sediments* (the mud and sand on the seabed) accumulate a cocktail of pollutants such as hydrocarbons and heavy metals. These toxic sediments are often *resuspended*, stirred back into the water column, during dredging and port maintenance, making pollutants available again to marine life and reintroducing them into circulation[773]. In effect, major ports function as nodal points in the global circulation of novel entities, concentrating risks that originate far beyond the local watershed.

- **Plastic pollution:** The shipping industry contributes significantly to plastic waste in the ocean. Fishing and aquaculture gear, much of it made from plastics like polypropylene ropes and nets, often ends up on the seabed and slowly breaks down into microplastics[774]. In 2022, 26% of the waste passively collected by fishermen was plastic[775]. One of the most damaging sources of plastic pollution is the loss of containers filled with plastic pellets, also known as *nurdles*, the raw material for most plastic products. The CSAV TOCONAO incident in December 2023, off the coast of Galicia in northwestern Spain, spilled around 26 tonnes of nurdles into the Atlantic. Millions of pellets washed up on Spanish and Portuguese beaches, smothering coastal ecosystems, contaminating fisheries, and sparking a major clean-up effort. Nurdles are often mistaken for food by fish, seabirds, and turtles, leading to starvation, poisoning, or death. Across Europe, shipping is estimated to account for 141–279 tonnes of pellet losses annually[776]. This is part of a wider global problem: once spilled, nurdles are almost impossible to remove from the environment, and they absorb toxic chemicals from seawater, becoming even more harmful to organisms that ingest them. Local ecological systems, from plankton to shellfish to fish, are directly impacted, with contamination moving up the food chain and eventually reaching human consumers.

- **PFAS pollution:** Per- and polyfluoroalkyl substances (PFAS), often called "forever chemicals," are widely used in ship lubricants, engine oils, firefighting foams[777], and PFAS-treated coatings. PFAS are linked to cancer, liver and thyroid disease, immune suppression, and adverse reproductive outcomes[778], such as reduced fertility, fetal growth restriction, and developmental problems in children[779]. Their extreme persistence means they accumulate in marine and human food webs, with long-term and still poorly understood consequences.

- **Hull and propeller cleaning:** Ship hulls are coated with *antifouling paints* designed to prevent biofouling. These paints often contain *biocides*, substances that kill or deter living organisms, as well as plastics and heavy metals such as copper and zinc. When hulls and propellers are cleaned in the water, these toxic coatings are released directly into the sea. A 2019 study estimated that 1,374 kilotonnes (kt) of plastic were used globally in marine paints, with around 66% (911 kt) leaking into the environment. Of this leakage, 29% comes from wear and tear during vessel operation, 34% during scrapping at end-of-life, and 26% during paint removal in dry docks[780]. The broader implication is clear: coatings designed to protect ships are in fact a major, ongoing source of novel entities entering marine ecosystems, and one of the least visible forms of plastic pollution.

- **Scrubber effluents:** To comply with fuel sulfur limits, many ships are fitted with *Exhaust Gas Cleaning Systems (EGCS)*, commonly known as scrubbers. Rather than cleaning the ocean, these systems "wash" sulfur and other pollutants out of exhaust gases using seawater, which is then discharged back into the sea as scrubber effluent. This effluent is acidic[781] and contains a mixture of heavy metals (zinc, vanadium, copper, nickel) and toxic organic pollutants (including polycyclic aromatic hydrocarbons such as phenanthrene, naphthalene, and fluorene)[782]. Acidification alters water chemistry and can reduce survival and reproduction in sensitive marine species[783], such as shellfish and plankton, while toxic metals and hydrocarbons accumulate in fish and other organisms.

- **Grey water:** *Grey water* is wastewater from sinks, showers, laundries, and galleys on ships. It contains detergents, soaps, grease, food waste, and other chemicals[784]. In most cases, grey water is discharged untreated into open waters, adding nutrient loads and toxic substances that can harm coastal and offshore ecosystems.

- **Bilge water discharges:** *Bilge water* collects in the lowest parts of a ship, mixing leaked lubricating oil, fuel residues, cleaning chemicals, detergents, and *sludge*, a semi-solid mixture of oil, water, and waste. Bilge water is one of the dirtiest waste streams on board, and although ships are supposed to treat it before discharge, illegal dumping of untreated bilge water into the ocean is widespread. This practice directly releases hydrocarbons and other pollutants into marine environments. Bilgewater generally picks up numerous contaminants such as lubricating oils and cleaning wastes.

- **Scale of discharges:** In European waters, an estimated 98% of all ship water discharges consist of wash waters from these scrubbers, the majority from open-loop systems (74%). The remaining 2% of discharges are primarily grey water (1.4%) and sewage (0.4%). This means that scrubber effluent is by far the largest source of operational liquid discharge from ships, transferring air pollution into the marine environment at massive scale[785].

Solutions and Maritime Interventions

As maritime shipping is a significant conveyor of novel entities, effective solutions must address not only end-of-pipe releases but also the logistics rules and market incentives that govern what moves through ports.

Global Plastics Treaty: The global plastics treaty is an international legally binding agreement being negotiated under UN leadership to address the global plastic pollution crisis. In March 2022, 175 nations agreed on a mandate to create a first-of-its-kind international legally binding instrument to end plastic pollution, with negotiations initially aimed for completion by the end of 2024. However, the first part of the fifth negotiating session, held in November 2024 ended in deadlock, with negotiators from over 170 countries failing to reach agreement[786]. The second part of the fifth session (INC-5.2) took place in August 2025 in Geneva, but likewise failed to reach consensus on critical issues, especially production limits and chemical regulation[787]. Negotiations remain paused, with no fixed date for resumption[788]. The urgency is clear: humanity was projected to consume over 500 million tonnes of plastics in 2024 alone, creating 400 million tonnes of plastic waste, and under business-as-usual scenarios, global plastic waste could almost triple to 1.2 billion tonnes by 2060[789]. We're creating plastic waste faster than nature can break it down (plastic takes 400–1000 years to decompose depending on its type and environmental conditions), so it accumulates permanently in the environment.

Stockholm Convention on Persistent Organic Pollutants (POPs): This treaty entered into force in 2004 and targets chemicals that are persistent, bioaccumulative, toxic[790], and capable of *long-range environmental transport*, meaning they can travel thousands of kilometres through air, water, or migratory species, and thus cannot be managed by any single country alone. Several chemicals listed under the Convention are found in materials and products used in shipping operations, including flame retardants (such as HBCDD), chlorinated paraffins, and PFAS compounds (such as PFOS in fire-fighting foams). These substances must be inventoried under ship recycling regulations[791].

IMO regulations: The International Convention on the Control of Harmful Anti-Fouling Systems on Ships (AFS Convention) prohibits the use of harmful antifouling systems on ships, most notably banning tributyltin (TBT) compounds that were found to cause severe hormonal disruption and reproductive damage in marine organisms, particularly mollusks[792]. This convention is already in force and has significantly reduced some toxic coatings.

Additional IMO instruments: The OPRC-HNS Protocol which governs preparedness and response to hazardous and NO_xious substance spills[793], and the London Convention and Protocol, which regulate the dumping of waste and chemicals at sea[794]. These protocols are active and have had measurable impact, though enforcement varies and continued vigilance is essential.

EU's REACH regulation: REACH (Registration, Evaluation, Authorisation, and Restriction of Chemicals) is the EU's main framework for managing chemical risks. It requires manufacturers/importers to register hazard information with authorities and aims to phase out substances of very high concern and enhance innovation in the EU chemicals industry[795].

The 'Need for Speed' report[796] published by the EEB (European Environmental Bureau), critically analyses the work of the European Chemical Agency (ECHA), which manages the technical and administrative aspects of the EU's chemicals legislation, primarily the REACH regulation. The report revealed that there is a stark contrast between the few short weeks it takes for companies to gain access to the European market, usually based on unreliable hazard data, and the years or even decades it takes authorities to restrict chemicals they learn are causing serious harm to people or the environment. Restricting chemicals in dangerous use in Europe takes 19 years and three months. Phasing out under the so called Authorisation process of the REACH regulation takes 22 years and 11 months while harmonising classification and labelling takes 19 years and five months to be completed.

The report's key recommendations include:

- writing strict and binding deadlines into law and ensuring accountability
- applying "no data, no market" and "zero tolerance to non-compliance" principles with harmonised and severe sanctions
- prioritizing protection over profits by using a precautionary approach and lowering the evidence level needed for authorities to restrict hazardous chemicals
- strengthening fast-track controls and banning groups of harmful chemicals in everyday products, and
- simplifying the system, for example, by defining and applying the "essential use" concept.

Advanced anti-fouling coatings: Biodegradable, self-polishing coatings that minimise release of toxic heavy metals and microplastics are being developed for shipping[797, 798]. Biomimetic non-toxic coatings, designed to mimic natural surfaces, (that contain no biocides or microplastics that can leach out) are also being tested[799].

Enhanced capture and waste treatment systems: Manual biofouling cleaning by divers has been found to generate more microplastics than cleaning using mechanised in-water cleaning (IWC) systems with debris capture. Transitioning to mechanised and automated cleaning with capture approaches could cut microplastic release by more than 90%[800], particularly for toxic antifouling residues.

Ballast water treatment systems, designed to prevent invasive species transfer, can introduce novel entities through chemical biocides[801]. These chemical treatments must be replaced by environmentally safe alternatives such as UV or filtration-based treatments.

Traditional methods for pollutant removal from air or water often face limitations in efficiency, selectivity, and sustainability. New materials, such as nanocellulose, metal-organic frameworks (MOFs), graphene-based composites, and biochar can support enhanced pollutant removal[802], from heavy metals and PFAS to difficult-to-degrade organic compounds. Innovative membrane technologies to remove hazardous pollutants from air and water are also being developed[803].

Shift to natural materials and circular approaches: The most effective strategy is to eliminate harm before it occurs. Designing out harmful substances from the outset, maximising material reuse, and implementing comprehensive waste capture systems that eliminate novel entity releases is key to protecting the planet and humans from the harmful impacts of novel entities entering the environment in the first place.

Current Contributions and Facts from the Port of Rotterdam

Rotterdam functions as one of the world's largest industrial complexes, hosting multiple power plants and oil refineries that convert crude oil into fuels and petroleum products for distribution across Europe[804]. Its petrochemical infrastructure inherently ties the port to the production, storage, and distribution of novel entities. The port's chemical handling operations include extensive tank storage facilities, specialised terminals, and multinational chemical companies managing vast volumes of hazardous substances, requiring robust environmental oversight. Additionally, this infrastructure forms a central link in the global value chain of novel entities: not only does it create pathways for spills, leaks, and emissions, but it acts as a key gateway for regional plastic and chemical throughputs. The vast quantities of plastics and chemicals distributed through the port to markets across Europe ultimately contribute to waste that degrades into the environment at end-of-life, spreading persistent pollutants into ecosystems, animals, and humans.

The Port of Rotterdam Authority has introduced several initiatives aimed at litter prevention and the collection of visible plastics[805]. These systems are *intended* to intercept large items, such as ropes, packaging, and plastic debris, before they fragment into microplastics or create navigational hazards. However, their actual effectiveness in reducing microplastic pollution is uncertain. A review by OceanCare (2023)[806] examined 38 clean-up technologies worldwide[807] and concluded that most are cost-inefficient, pose environmental risks, and risk distracting from systemic and local solutions. The report recommends these technologies should only be considered in cases of extremely polluted ecosystems and be subject to independent prior mandatory Environmental Impact Assessments and rigorous and continuous monitoring of environmental impacts with clear checks-and-balances to ensure they do not create new environmental disruption.

One example of regional collaboration is the Rijn-Maas PLASTIVAL[808] a multi-stakeholder event focused on tackling plastic pollution in the Rhine-Maas delta. Plastic waste was analyzed from 16 sites across the delta, with students, professionals, volunteers, and researchers jointly investigating half of these locations to better understand the scale and diversity of the plastic pollution problem. Participants developed solutions ranging from local initiatives like neighborhood plastic collection teams to larger-scale collaborations between companies and governments for sustainable production chains[809]. The festival emphasised that regional cooperation against plastic pollution is essential to achieve a plastic-free delta. Increasing the number and scale of such local initiatives will be key to preventing plastic pollution in the port area[810].

Recommendations for the Port of Rotterdam

- **Create a Novel Entity Baseline and Monitoring Programme:**
  Conduct a full audit of industrial, shipping, and wastewater discharges into the port to identify the major contributors of novel entities, especially PFAS, plastic pellets (nurdles), microplastics, tire wear particles, and flame retardants. Existing monitoring programmes should be expanded to cover all hazardous chemicals and pollutants handled within the port complex, including comprehensive reporting and inventories of inputs and outputs.

- **Establish transparency / reporting requirements:**
  Require all port industrial complex tenants to report on quantities of toxic substances they process and release. Transparent reporting is a prerequisite for accountability and for setting effective reduction targets.

- **Create a Digital Chemical Passport System:**
  Build on the port's digital supply chain initiatives by introducing a system to track chemical substances as they move through terminals and facilities. This would enable full lifecycle assessments, provide data for monitoring compliance, and support targeted pollution mitigation efforts.

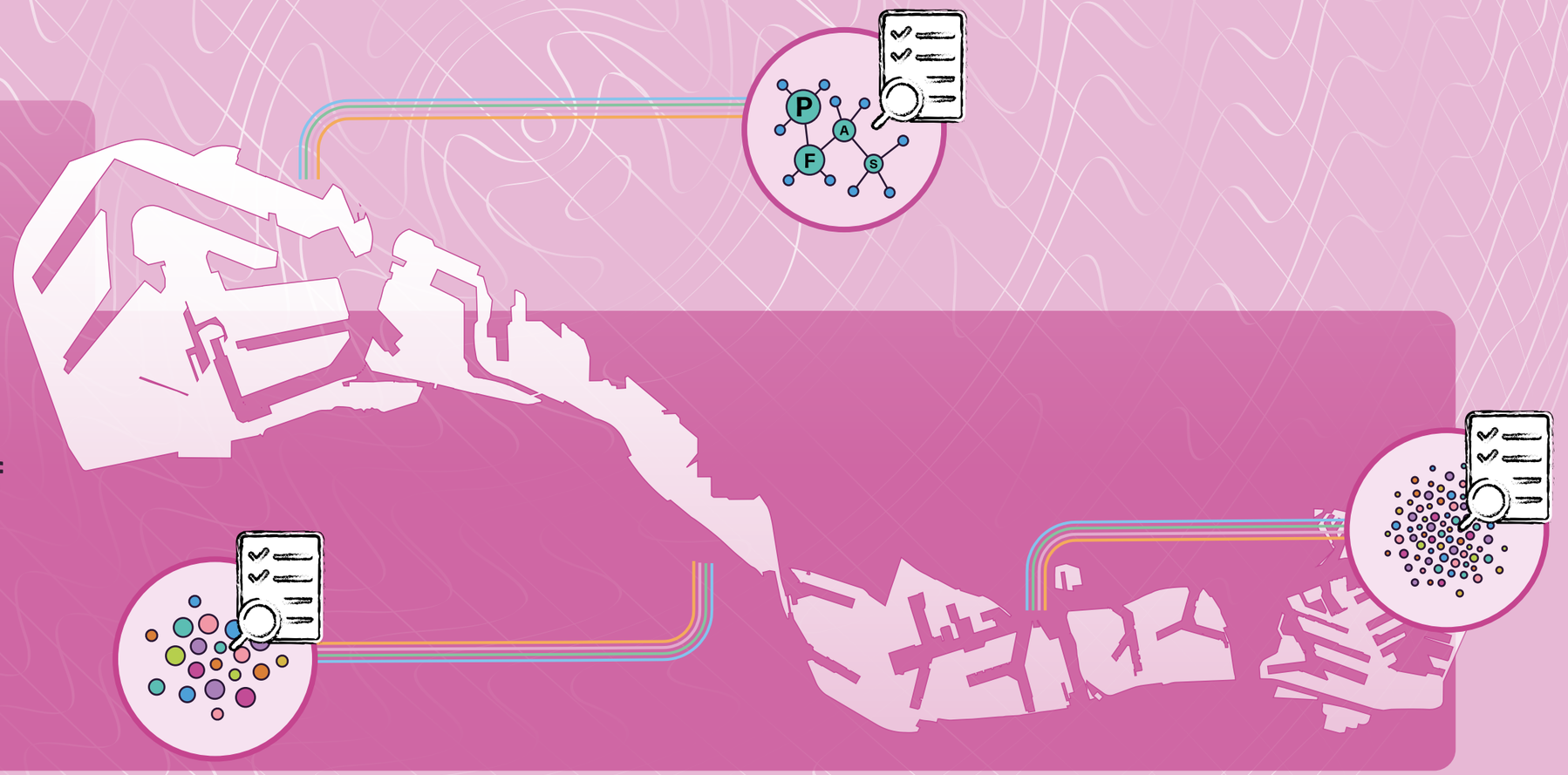
- **Enhanced capture and waste treatment infrastructure:**
  Develop or mandate the development of centralised facilities for managing microplastic-contaminated water from in-water cleaning operations, and incorporate advanced filtration and treatment technologies for different hazardous substances. Establish clear guidelines and best practices for handling and disposing of waste collected from clean-up operations, ensuring that pollution is not simply shifted from one medium to another.

- **Support innovation:**
  Promote the development and adoption of nature-based materials, biodegradable chemicals, and advanced antifouling technologies. Rotterdam could position itself as a demonstration site for sustainable chemistry, featuring bio-based feedstocks, closed-loop industrial processes, and zero-waste production models.

- **Address the PFAS dilemma through an 'Essential Use' framework:**
  proton Exchange Membrane (PEM) electrolysers and fuel cells, a key technology for producing and using hydrogen, contain a fluoropolymer[811] (type of PFAS) membrane. This illustrates the tension between environmental protection and renewable energy goals. PFAS materials are also used in a wide range of critical sectors, including the semiconductor industry, which supplies components for microelectronics, and in numerous medical products[812] where no viable substitutes currently exist. In such cases, some limited capacity for PFAS use may remain unavoidable until viable alternatives are developed. However, PFAS and other toxic materials used in non-essential products and processes, such as cookware coatings, textiles, or single-use consumer goods, must be phased out. Distinguishing between essential and non-essential uses is therefore a prerequisite for transitioning to a safe operating space within the planetary boundaries.

The Port of Rotterdam

Maintain a novel entities monitoring programme, including a full audit of industrial, shipping, and wastewater discharges into the port to identify the major contributors of novel entities, especially PFAS, plastic pellets (nurdles), microplastics, tire wear particles, and flame retardants.



Recommendations for Policymakers

Policy must reflect that controlling what is transported, how it is handled, and under which conditions it can enter markets is as important as cleaning up operational discharges.

- **Incentives for pollution reduction:**
  Introduce tax incentives for vessels and port operations that can demonstrate measurable reductions in novel entity discharges, paired with penalties for activities with high negative impact. This creates clear financial drivers for cleaner practices.
- **Enhanced R&D investment programme:**
  Expand funding programmes for innovation in biodegradable marine coatings, advanced monitoring technologies, and novel treatment systems. Public investment should prioritise scalable solutions that can be rapidly adopted across the maritime sector.
- **Expand existing monitoring networks:**
  Extend current microplastics monitoring into a comprehensive system covering all major categories of novel entities in coastal waters, especially in areas of heavy shipping traffic and industrial activity. This expansion should be aligned with, and built upon, existing OSPAR and EU monitoring frameworks to avoid duplication and ensure comparability.
- **Revision of Maritime Environmental Directives:**
  Advocate for strengthening the Marine Strategy Framework Directive to include specific novel entity reduction targets and enhanced monitoring requirements for shipping-related pollution. Stronger directives will provide the legal backbone for coordinated EU-wide action.
- **REACH Regulation Enhancement:**
  Push for specific provisions covering shipping-related sources of novel entities, including marine coating chemicals and ballast water treatment by-products. Simplify and accelerate the processes for phasing out hazardous chemicals from the market.
- **Ban easily substitutable uses:**
  Set bans on using toxic chemicals in applications where sustainable alternatives already exist, particularly in consumer-facing products such as cosmetics, household items, food packaging, and textiles. These bans deliver immediate public health and environmental benefits while preserving capacity for essential uses in pharmaceuticals and clean energy technologies which are essential for maritime decarbonisation.
- **Focus on prevention:**
  Allocate resources towards initiatives that stop pollution at source rather than relying on clean-up or recycling. Recycling cannot solve the plastics crisis: only 9% of global plastic waste is recycled (15% is collected for recycling but 40% of that is disposed of as residues). Another 19% goes directly to incineration, 50% ends up in landfill and 22% evades waste management systems and goes into uncontrolled dumpsites, is burned in open pits or ends up in terrestrial or aquatic environments, especially in poorer countries[813]. Preventing production and release is therefore the most effective pathway.

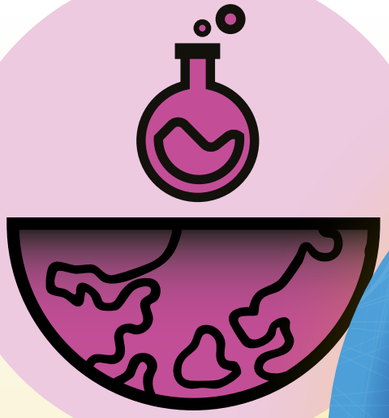
Conclusion and Call to Action

The Novel Entities planetary boundary represents one of the most complex environmental challenges of our time, with the maritime sector serving as both a significant contributor to the problem and a critical leverage point for solutions. The industry not only generates novel entities directly through its operations but also serves as a critical conduit in global supply chains that drive boundary transgression.

Addressing this challenge requires a dual approach. On the one hand, simple prohibitions on clearly harmful substances and practices, such as toxic antifouling paints, non-essential PFAS uses, or easily substitutable consumer chemicals, can deliver immediate and proven benefits. On the other hand, systemic transformation demands navigating complex trade-offs, for example where hazardous substances are embedded in clean energy technologies, semiconductors, or medical products with no safe alternatives yet available.

Urgent, coordinated action across the entire value chain is therefore essential, from individual port operations to global regulatory frameworks. The Netherlands has shown leadership in championing sustainable chemistry, but this must now be matched with targeted measures addressing the maritime sector's novel entity contributions.

Rotterdam, as Europe's largest port and one of the busiest in the world, has a unique opportunity to demonstrate that even the most complex industrial hubs can lead in protecting planetary health. The choices made in the next few years will determine whether the maritime sector deepens boundary transgression or becomes a catalyst for steering back towards the safe operating space that sustains human civilisation and natural ecosystems alike.



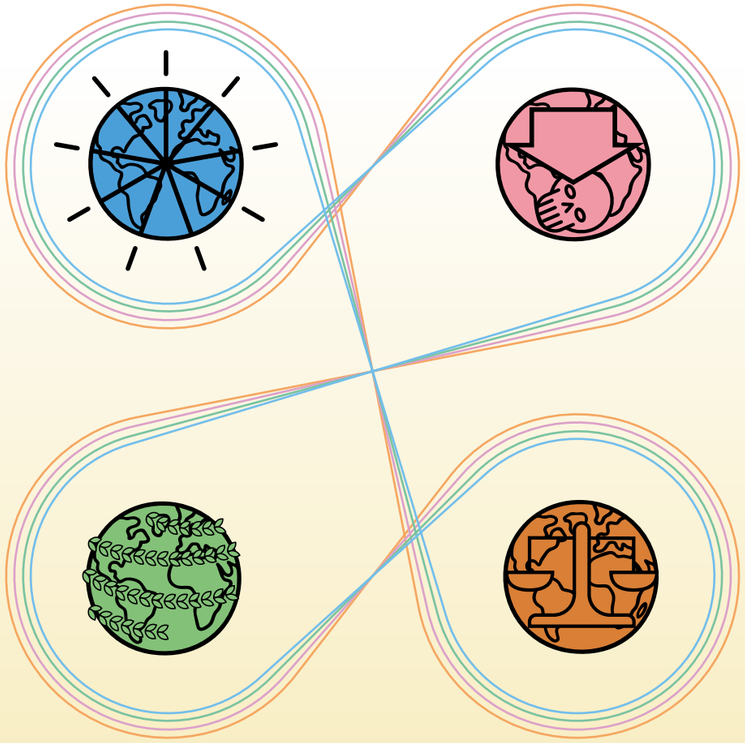
"The hazards and risks of chemicals are currently assessed substance by substance. ... Concerns still remain that analysing individual chemicals alone does not provide sufficient security and that the combination effects of chemicals should be addressed in a more systematic way."
European Chemicals Agency (ECHA) on combined effects of chemicals.

CH11 Conclusion

From Possibility to Practice: Delivering Rotterdam's One Planet Port

This Vision Report began with a simple proposition: a great port can deliver shared prosperity by operating within planetary limits. This challenge presents Rotterdam with a once-in-a-millennium opportunity to pioneer a new model of maritime operations and infrastructure. It offers a chance to look beyond the traditional greenhouse gas reduction and environmental sustainability lens, to a more holistic, systemic approach that enables operations within planetary limits, while preserving economic vitality. Our analysis confirms the opportunity and clarifies the path. Rotterdam can move first, and when it does, the benefits ripple across Europe: cleaner air and water, more secure value chains, and good jobs in circular and regenerative industries.

Delivering this means we:



1. Design and operate within planetary limits.

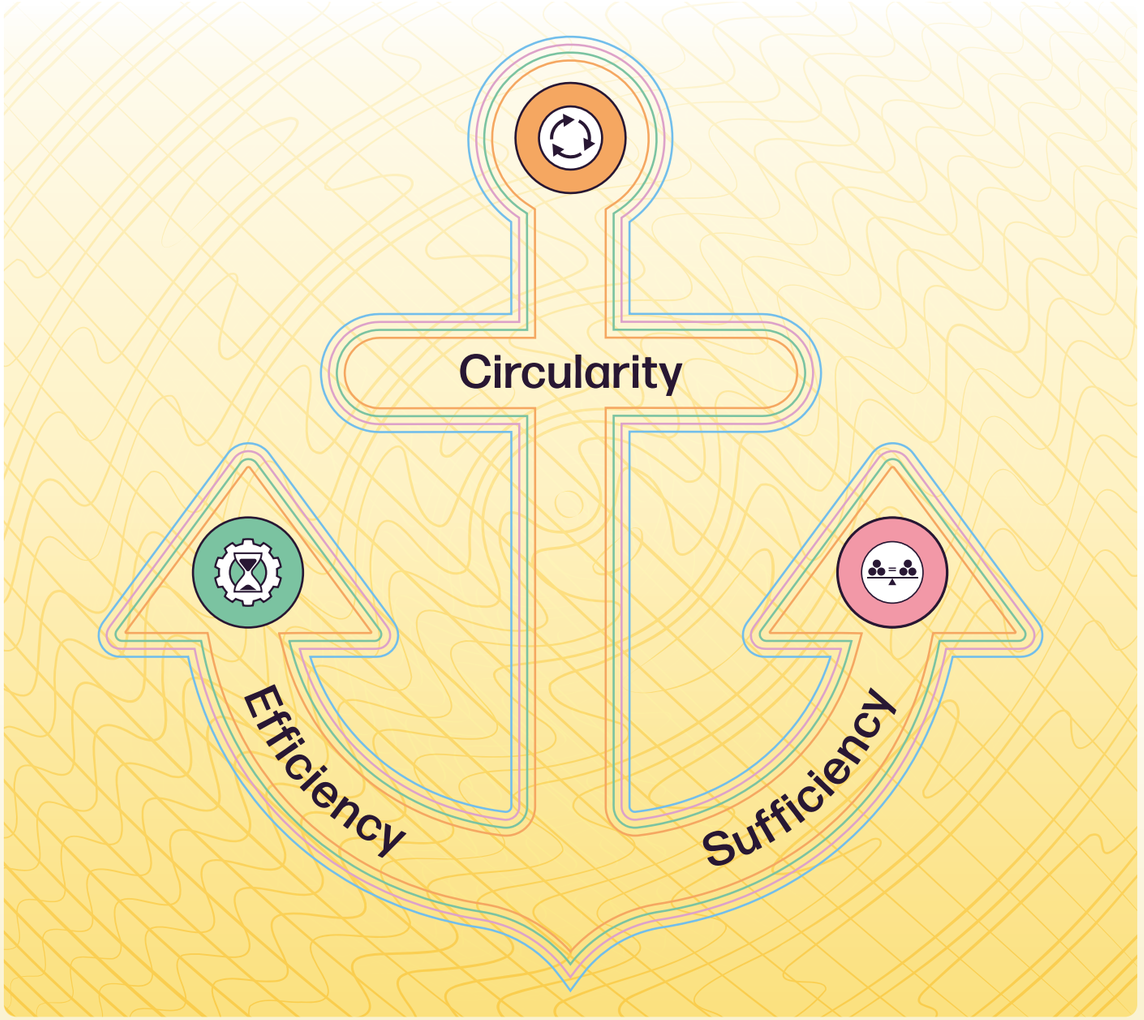
2. Prioritise absolute reductions in harm.

3. Make nature an ally.

4. Ground value chains in transparency and fairness.

These principles are operationalised through three anchors repeated in this report:

Figure 11.1 Conceptual anchor linking circularity, efficiency, and sufficiency



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Rotterdam's Impact Extends Far Beyond Direct Emissions, Requiring System-wide Transformation

Rotterdam's true climate and materials impact extends far beyond its direct emissions. The CO_2 emissions from its own operations, shipping, and the port and industrial complex (PIC) in 2024 and 2023 amounted to ~2.2 million tonnes[814]. The throughput of the port in 2024 was 435.8 million tonnes[815], including:

- Dry bulk (iron ore, scrap, agri bulk, other): 71.2 million tonnes
- Liquid bulk (crude oil, mineral oil products, LNG, other liquid bulk): 200 million tonnes
- Containers: 133.4 million tonnes (13,800,000 TEU)
- Breakbulk (Roll-on/Roll-off, general cargo): 31.2 million tonnes

In 2024, 9.06 million tonnes of fossil fuels were bunkered in the Port of Rotterdam[816], in addition to 757,300 tonnes of bio-blended fuels[817].

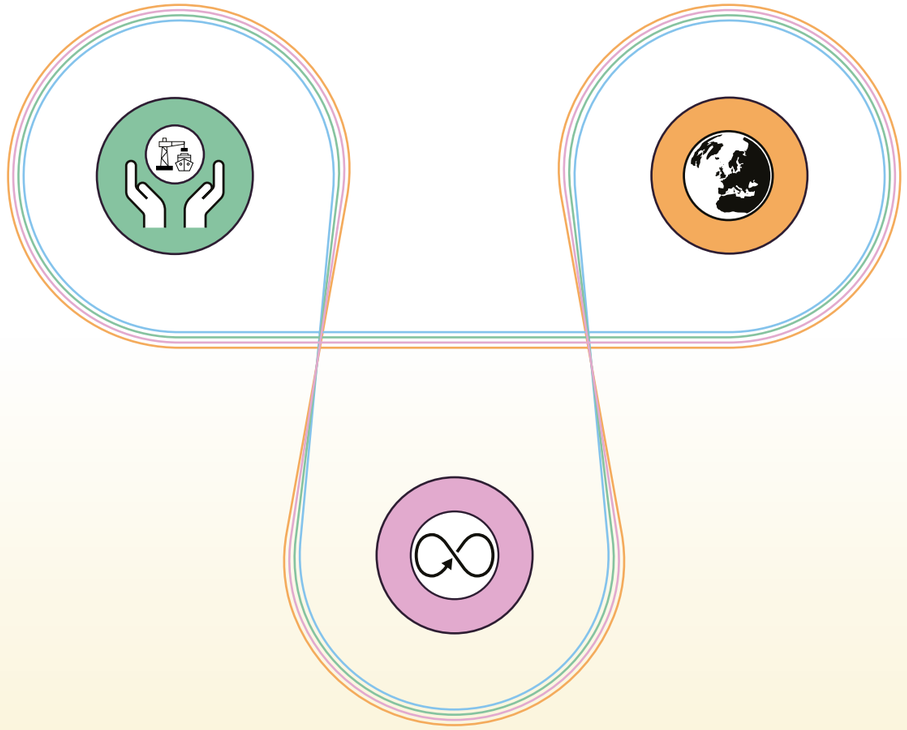
Nitrogen pollution, biodiversity loss, freshwater depletion, and chemical contamination similarly extend throughout global value chains that Rotterdam enables, far beyond the Netherlands' borders. If extended to all materials flows, the impact of Rotterdam outpaces its size by several orders of magnitude.

To operate within planetary boundaries, ports must recognise that their influence extends far beyond how goods are moved, to what cargoes flow through global value chains. As introduced in Chapter 1, throughput impacts capture the full environmental pressures linked to the materials and products passing through a port from the embedded impacts of producing those goods, to the supply-chain impacts of transporting them, and the impacts from their eventual use or disposal. The transformation ahead requires decision-makers to treat throughput impacts as a central metric of port sustainability. This means evaluating the ecological consequences of cargo profiles, prioritising essential and low-impact value chains, and actively phasing out high-impact throughput that drives planetary boundary overshoot. By incorporating throughput impacts into access decisions, infrastructure planning, and material-energy accounting, ports can move from being passive conduits of material flows to proactive stewards of regenerative trade systems.

Addressing these interconnected impacts requires:

Recognising the holistic role that the Port of Rotterdam plays in the global economy

Reimagining the port's role in a future that ensures long-term human and planetary well-being



Intentionally designing iterative learning loops that improve resilience and create cascading effects to ports across the globe

The Principles of Efficiency, Sufficiency, Comprehensive Accounting, and Throughput Impacts Must Guide Transformation

Our analysis culminates in the following foundational principles that must guide Rotterdam's transformation towards operating within the planetary boundaries:

- **Efficiency within ecological limits**: Optimising resource use and operational performance while ensuring all activities remain within scientifically established planetary boundaries. Efficiency here means designing systems that minimise total material and energy inputs and maximize beneficial outcomes for human well-being, ecological integrity, and long-term economic resilience.

- **Sufficiency as a guiding framework:** Orient port activities on meeting genuine societal needs rather than facilitating unlimited growth in material throughput based on unidimensional metrics such as GDP. Sufficiency calls for a critical distinction between essential trade that supports collective well-being and resource-intensive consumption that accelerates planetary overshoot.

- **Net Material-Energy Balance Accounting:** Establishing comprehensive accounting systems that track all material and energy flows associated with port operations, planetary boundaries impacts embedded in value chains, as well as throughput-related impacts. This approach provides the foundation for Rotterdam to modify its activities in ways that contribute to global net-negative impacts and regenerative material cycles, rather than reinforcing extractive practices that exceed planetary limits or serve purely financial gain.

- **Throughput Impacts:** The full planetary-boundary pressures linked to the materials and products that move through the Port of Rotterdam. They include the embedded impacts of producing those goods (such as raw material extraction, energy use, chemical inputs, land-use change, and waste generation), the supply-chain impacts of transporting them across global value chains (primarily maritime, but also rail, road, and inland waterway transport), and the impacts from their eventual use or disposal (such as emissions from fossil fuel combustion, plastic pollution, nutrient runoff, and end-of-life waste). Looking at throughput impacts shows that port sustainability depends not only on how we ship (fuel, vessel design) but also what we ship (cars, crude oil, metals, plastics, food, electronics) and how those value chains drive pressures on planetary boundaries.

Port sustainability isn't just about how we ship – it's about what we ship, and how entire value chains push against planetary boundaries.

The table below shows how today's approaches evolve into a system that is cleaner, fairer, and more resilient.

Table 11.1 Comparison of current sustainability approaches and a Net Material–Energy Balance Accounting & Planetary Boundaries framework

System Dimension / Focus Area	Current Sustainability Approaches	Net Material-Energy Balance Accounting & Planetary Boundaries Framework
Greenhouse gas and aerosol emissions	Zero Scope 1 & 2 by 2050	Net climate-neutral operations across Scope 1, 2 & 3 and **throughput emissions** well before 2050. Driven by absolute emission and throughput reductions alongside circular and regenerative practices
Nitrogen, and other planetary flows (to air, land and water)	Typically excluded from port planning	Integrated assessment preventing boundary overshoot
Fossil fuel phase-out	Prolonged and delayed transition with largely unchanged fossil throughput	Complete fossil fuel phase-out enabling net negative material balance
Complete value chain accountability, including throughput impacts	Focus on direct operational control	Full accountability for embedded impacts based in the cargo throughput and upstream, operational, and downstream impact across transport value chains
Global climate alignment	1.5°C overshoot likely, with several sensitive tipping points being breached	Aligned with the rapid reduction required to stay within the remaining 130 Gt CO^2 carbon budget required to limit warming to 1.5°C[818], a target now expected to be exhausted within the next three years at current emission rates
Decision-making frameworks	Single-issue optimisation	Systemic assessment across all nine boundaries
Underlying economic principles	Growth-dependent throughput maximisation	Efficiency, Sufficiency, and Net Material-Energy Balance Accounting
Risk management and mitigation frameworks	Rigid/linear/sequential, reactionary approaches, systems are unsuitable for dealing with shocks[819]	Flexible systems prepared for uncertainty: Structures that can respond to multiple possible futures rather than single predictions. Modular design and decentralised decision-making enable experimentation, supported by feedback mechanisms that drive continuous improvement[820].

Source. One Planet Port Foundation (2026), original synthesis. Licensed under CC BY 4.0.

Our Nine-point Vision for a Regenerative Port, Aligned with the Nine Planetary Boundaries

We envision the Port of Rotterdam as a regenerative port that actively restores ecological health while maintaining essential social and economic functions. The purpose of all port transformation moving forward is to achieve holistic well-being and societal prosperity that can be sustained for generations to come.

1. **From emissions reduction to safe, net-negative impact:** Moving beyond narrow greenhouse gas reduction targets towards a comprehensive strategy that not only minimises emissions but also enables safe levels of emitting within planetary limits. This means achieving deep absolute reductions across all port operations and throughput activities.

2. **From single-issue solutions and siloed efficiency to systemic coherence:** Ensuring that solutions or improvements in one boundary (like climate) do not inadvertently undermine others (such as nitrogen cycles or biodiversity) by adopting integrated decision-making frameworks that assess cascading effects across all nine Earth system processes.

3. **From a prolonged and delayed transition to complete fossil fuel phase-out:** Looking beyond scenarios that see a continued use of fossil fuels and their transport, to eliminating fossil fuel throughput entirely, urgently and decisively.

4. **From direct operational focus to complete value chain responsibility:** Expanding responsibility beyond the port's direct footprint to include throughput emissions (upstream, downstream) and associated impacts. A truly one-planet-aligned port recognises its enabling role in global production and trade systems and takes shared accountability for reducing their cumulative pressures.

5. **From linear throughput to circular and regenerative systems:** Transitioning port infrastructure from facilitating one-way material flows to supporting regenerative and circular economy principles. This means shifting the port's core functions away from processing raw, extractive materials towards supporting reuse, repair, remanufacturing, and other circular activities.

6. **From growth-dependent throughput maximisation to sufficiency principles:** Reorienting port operations towards meeting genuine societal needs rather than unlimited material growth, prioritising efficiency, sufficiency, and net material-energy balance accounting over volume-based metrics.

7. **From isolated infrastructure to integrated well-being:** Designing every port development to contribute simultaneously to planetary health and community prosperity. Through the Planetary and Human Well-Being Framework, decisions balance ecological regeneration, social equity, and long-term economic resilience, moving beyond short-term profit towards enduring societal value for generations to come.

8. **From linear risk management to adaptive resilience:** Moving beyond rigid systems and reactive planning towards flexible, scenario-based frameworks. Continuous feedback loops enable the port to learn from change and turn disruption into opportunity.

9. **From reactionary policy and defensive planning to transformative adaptation:** Shifting from merely protecting existing systems against shocks to building port capacity that thrives in uncertainty. A one planet port uses crises as opportunities for redesign, learning, adapting, and strengthening with each disruption.

Port access decisions must align planetary boundary adherence with human well-being

Rotterdam must move beyond the current model of granting port access based solely on commercial viability. Infrastructure use and spatial access should instead be conditional upon a holistic assessment of each activity's impact across all planetary boundaries. We propose implementing a **Planetary and Human Well-Being Framework** that conditions access to port infrastructure on demonstrated contributions to both ecological health and community prosperity. This means prioritising organisations that operate within planetary boundaries, support ecosystem restoration, and create stable, well-paid, and meaningful employment aligned with long-term societal resilience. Conversely, entities that systematically breach planetary boundaries, externalise environmental or social costs, or prioritise short-term financial returns over long-term well-being should face graduated restrictions on infrastructure and spatial access.

Implementation of the ***Planetary and Human Well-Being Framework:*** All prospective port tenants would undergo well-being assessments encompassing their full value chain impacts on planetary boundaries and local communities.

Existing lease renewals would incorporate graduated well-being performance standards, with preferential terms for organisations demonstrating measurable contributions to ecological and social health. Port authorities could establish well-being performance tiers, offering enhanced access, reduced fees, or priority berthing to entities meeting higher standards. Large multinational corporations would face enhanced scrutiny given their large scale and system-wide impacts. This approach transforms ports from a passive facilitator of any profitable activity into an active steward of trade that regenerates ecosystems, strengthens communities, and aligns economic activity with planetary stability.

From Vision to First Implementation

The transformation to a *one planet port* must now move from principle to practice. The following near-term actions can be initiated within the next 12 months to begin operationalising this Vision Report. Each step reflects one or more elements of the nine-point vision, turning long-term principles into measurable progress and building early confidence in Rotterdam's leadership.

1. **Adopt the Planetary & Human Well-Being Framework for all new tenant decisions:** Embed planetary-boundary and well-being assessments into every new lease and concession. Make access to port infrastructure conditional on demonstrable contributions to ecological regeneration and community prosperity.

2. **Publish a port-wide Energy-Material Flow Account and commit to annual updates:** Track all material and energy flows across operations and throughput. This transparency will provide the evidence base for sufficiency-driven planning and identify where absolute reductions deliver the greatest benefits.

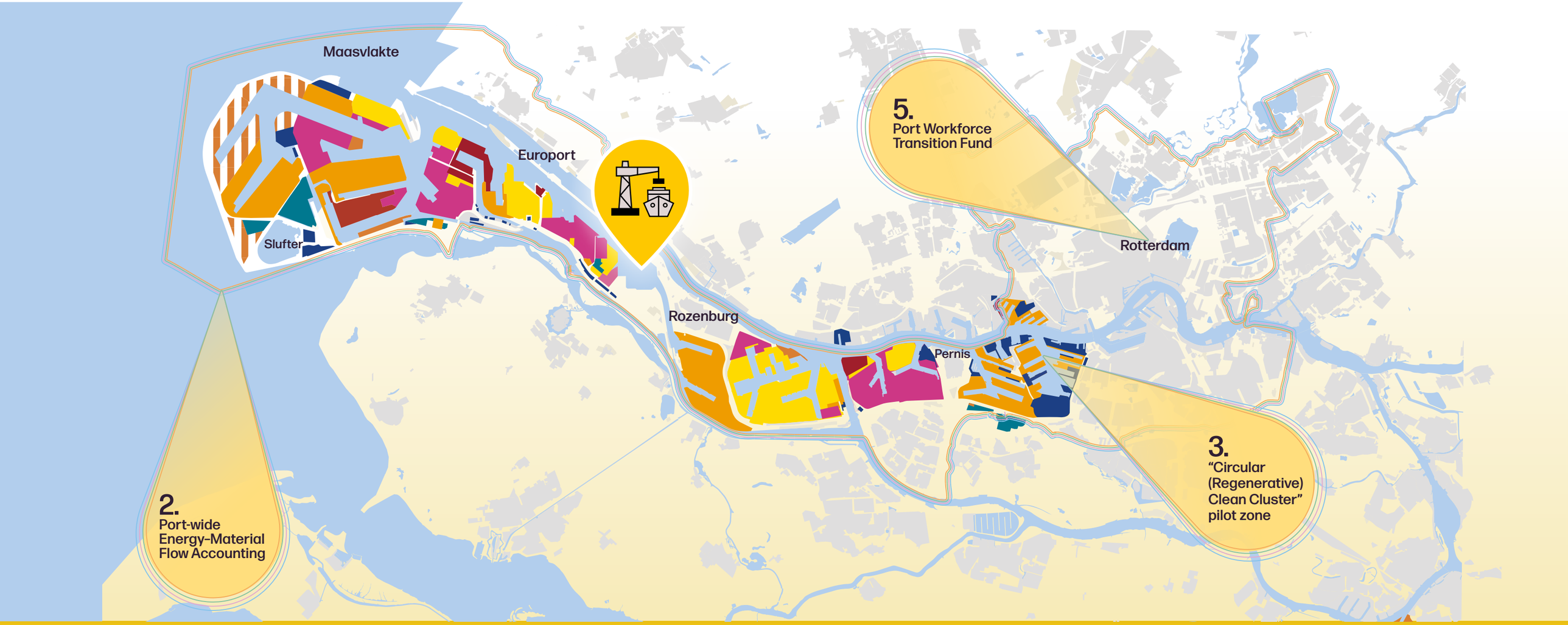
3. **Launch a "Circular Clean Cluster" pilot zone:** Designate a section of the port for circular industry clusters focused on repair, reuse, remanufacturing, and nature-based adaptation. The pilot will showcase how sufficiency-based value chains can generate high-quality employment and reduce resource intensity.

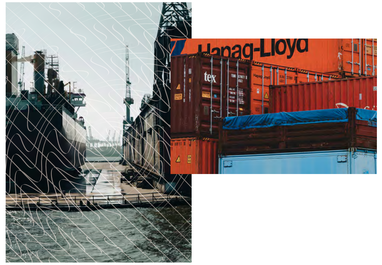
4. **Apply sufficiency-based access criteria to cut high-impact throughput:** Introduce clear ecological and social performance standards for activities with the largest embedded emissions. Prioritise essential trade that supports societal well-being, while phasing out or redesigning non-essential, resource-intensive throughput.

5. **Establish a Port Workforce Transition Fund:** Support reskilling and secure livelihoods for workers shifting into electrification, efficiency retrofits, and circular processing. Launch with a goal of training workers in the first year in partnership with unions, educational institutions, and industry.

These initiatives demonstrate that planetary alignment and economic vitality can advance together. They turn the Vision Report from a strategic framework into an implementation agenda, showing that Rotterdam's transition is already underway.

Figure 11.2 The Port of Rotterdam





The Work Ahead

This Vision Report establishes direction; detailed implementation requires collaborative expertise. Our planetary boundaries framework intentionally provides systems-level thinking that complements rather than duplicates existing regulatory mechanisms like CSDDD, GHG Protocol, and EU Taxonomy. The next phase of our work involves deep-dive analyses with sector experts and policymakers to examine how these frameworks align, where gaps exist, and how regulations can be streamlined to support planetary boundary compliance.

We recognise that Rotterdam Port Authority pursues numerous sustainability initiatives that may not be fully captured in public documentation. Our recommendations build on this foundation rather than dismissing existing efforts. Where our analysis appears to overlook current activities, we welcome dialogue to understand how ongoing work aligns with planetary boundaries thinking and where collaborative enhancement opportunities exist.

OPP offers this report as a starting point for ongoing collaboration, not a final blueprint. We invite researchers, regulators, industry practitioners, and community stakeholders to engage with these ideas, challenge assumptions, contribute expertise, and help translate directional vision into implementable strategies. The transition to a one planet port requires collective intelligence and sustained partnership across all stakeholder groups.

A Bright Path Forward

OPP stands ready to support Rotterdam's transformation through applied research, community collaboration, and evidence-based policy development. Our next phase of work will focus on translating the principles and recommendations of this Vision Report into practical actionable implementation pathways, relevant not only for Rotterdam, but for port communities worldwide seeking to operate within planetary limits.

The stakes could not be higher. Environmental destabilisation breeds uncertainty, which, in turn, erodes the security and prosperity that European societies have built over generations. Transforming Rotterdam into a one planet port is not merely an act of adaptation; it is an act of prevention, addressing the root causes of planetary disruption rather than its symptoms.

The journey from vision to implementation has already begun. We invite all stakeholders to join us in building a regenerative maritime ecosystem, one that restores the foundations of life, supports human dignity, and secures a stable and liveable future for generations to come.
A One Planet Port.

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A One Planet Port vision: Port of Rotterdam, thriving within the Planetary Boundaries.

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