Beyond carbon: Environmental considerations of ammonia as a marine fuel

Technical Seminar on the Use of Ammonia as Marine Fuel

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Ammonia can help decarbonize shipping

Ammonia can help decarbonize shipping, but only if its full lifecycle impacts are understood and effectively managed

Agenda: Three main questions

1. What **reactive nitrogen emissions** can arise from ammonia marine fuel**?**

2. What are their **marine-ecosystem and climate** consequences**?**

3. What **controls** are needed to preserve ammonia's environmental benefits**?**

1. Reactive nitrogen emissions from ammonia

Reactive nitrogen (Nr): a major environmental challenge

Reactive nitrogen is any form of nitrogen that can readily interact with living things and the environment.

*Around **80% of human-produced reactive nitrogen** is lost to the environment each year contributing to climate change, air and water pollution, and biodiversity loss*

Potent, long-lived GHG

Ozone-depleting substance*

N_2O

Air pollutants

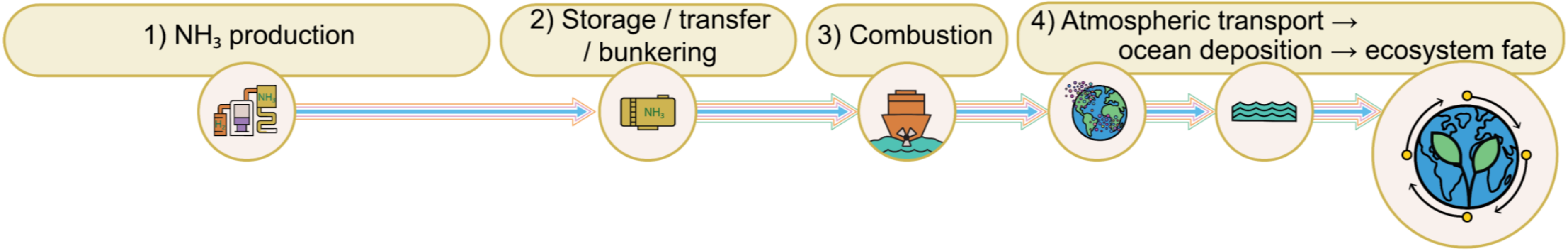
Short-lived climate forcers

NOx

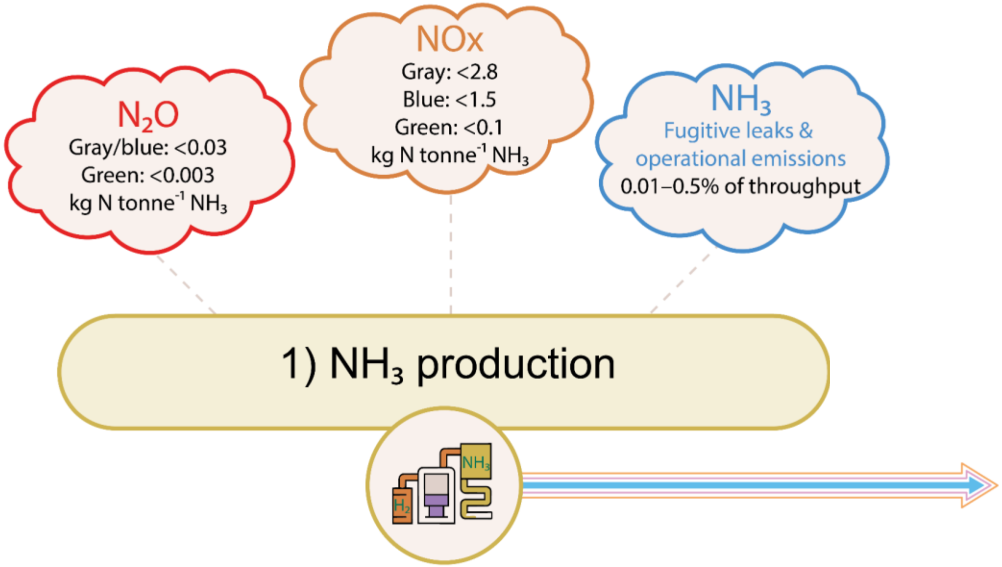
NH_3

Sources: UN Environment Programme; Gilliam et al. (2026), *Frontiers in Marine Science;* * not controlled under the Montreal Protocol

Ammonia marine fuel value chain

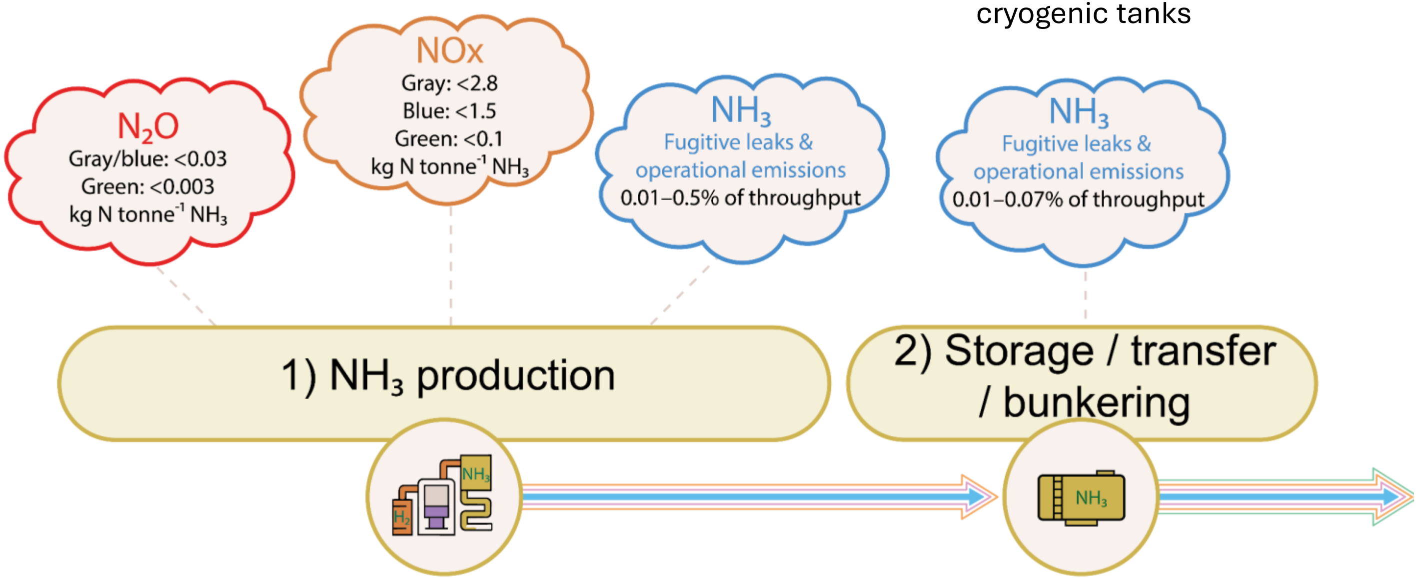


N_2O/NOx sources:
Combustion used for hydrogen production, process heat, and electricity

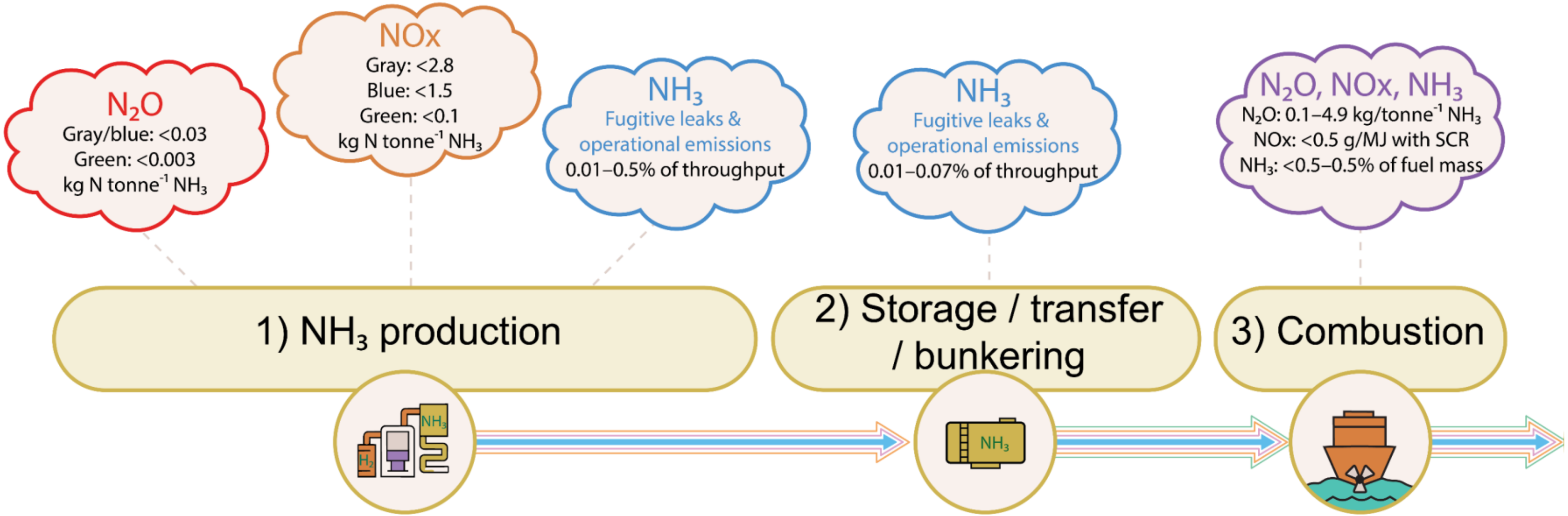


Source: Gilliam et al. (2026), *Frontiers in Marine Science*

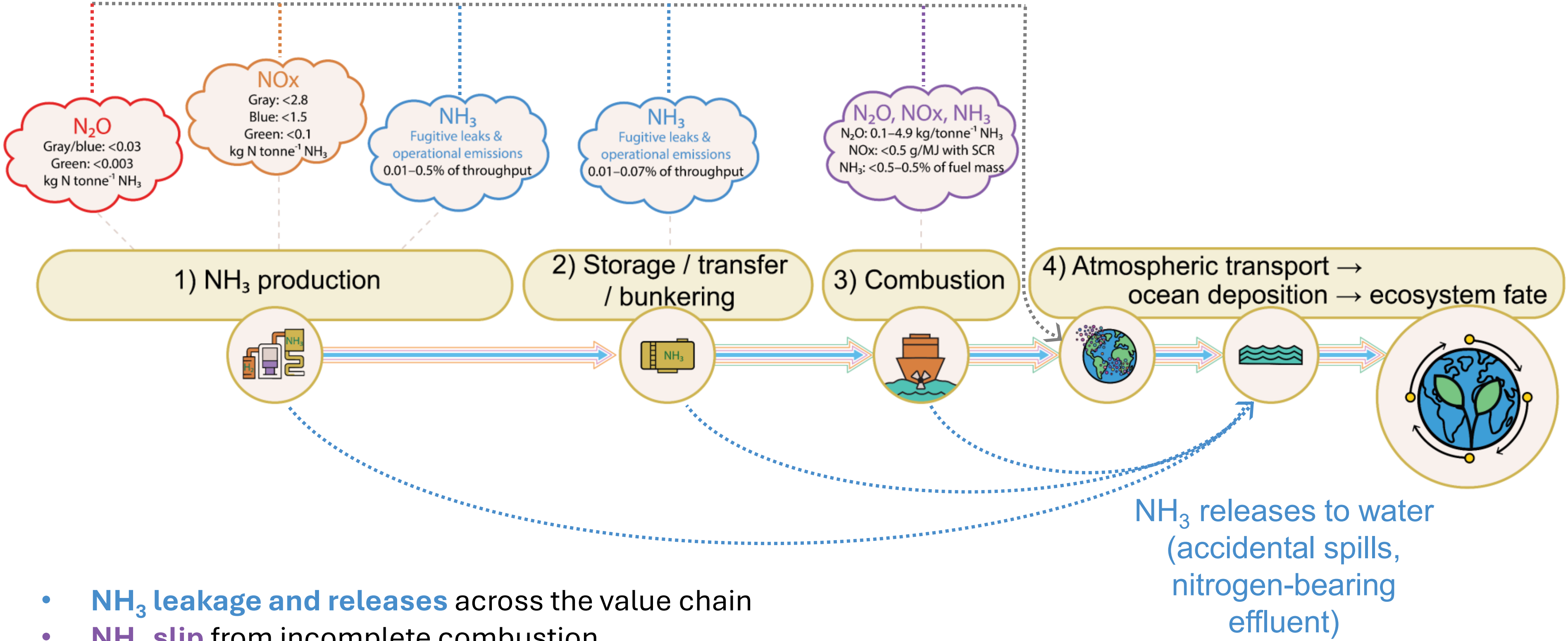
NH_3 sources:
Fugitive: tank breathing, pressure relief events, loading and unloading ops., pipeline and transfer system leaks, emergency venting.
Boil-off gas: heat ingress into cryogenic tanks



Source: Gilliam et al. (2026), *Frontiers in Marine Science*

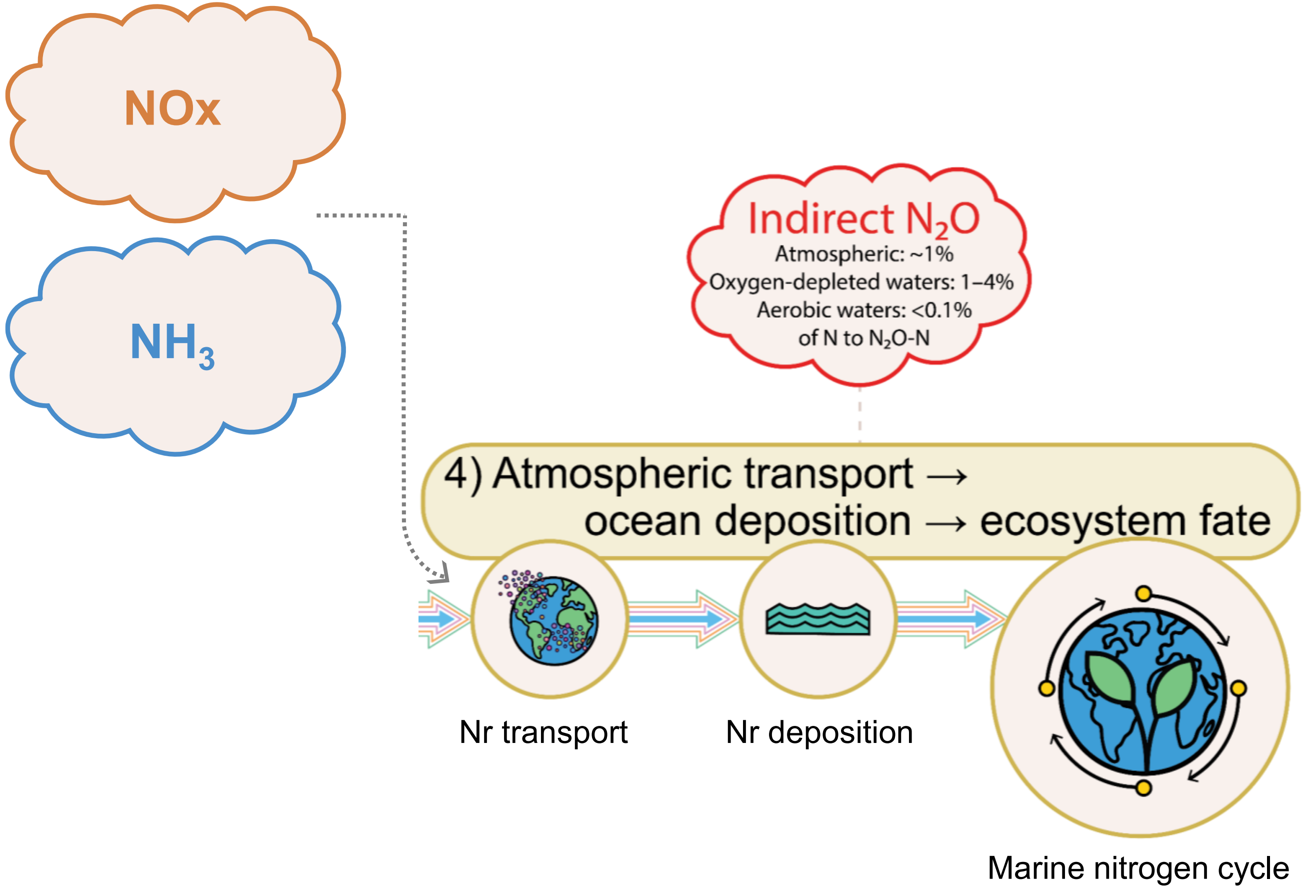


N2O
Gray/blue: <0.03
Green: <0.003
kg N tonne-1 NH3
NOx
Gray: <2.8
Blue: <1.5
Green: <0.1
kg N tonne-1 NH3
NH3
Fugitive leaks &
operational emissions
0.01–0.5% of throughput
NH3
Fugitive leaks &
operational emissions
0.01–0.07% of throughput
N2O, NOx, NH3
N2O: 0.1–4.9 kg/tonne-1 NH3
NOx: <0.5 g/MJ with SCR
NH3: <0.5–0.5% of fuel mass
1) NH3 production
2) Storage / transfer / bunkering
3) Combustion
NH3
H2
NH3



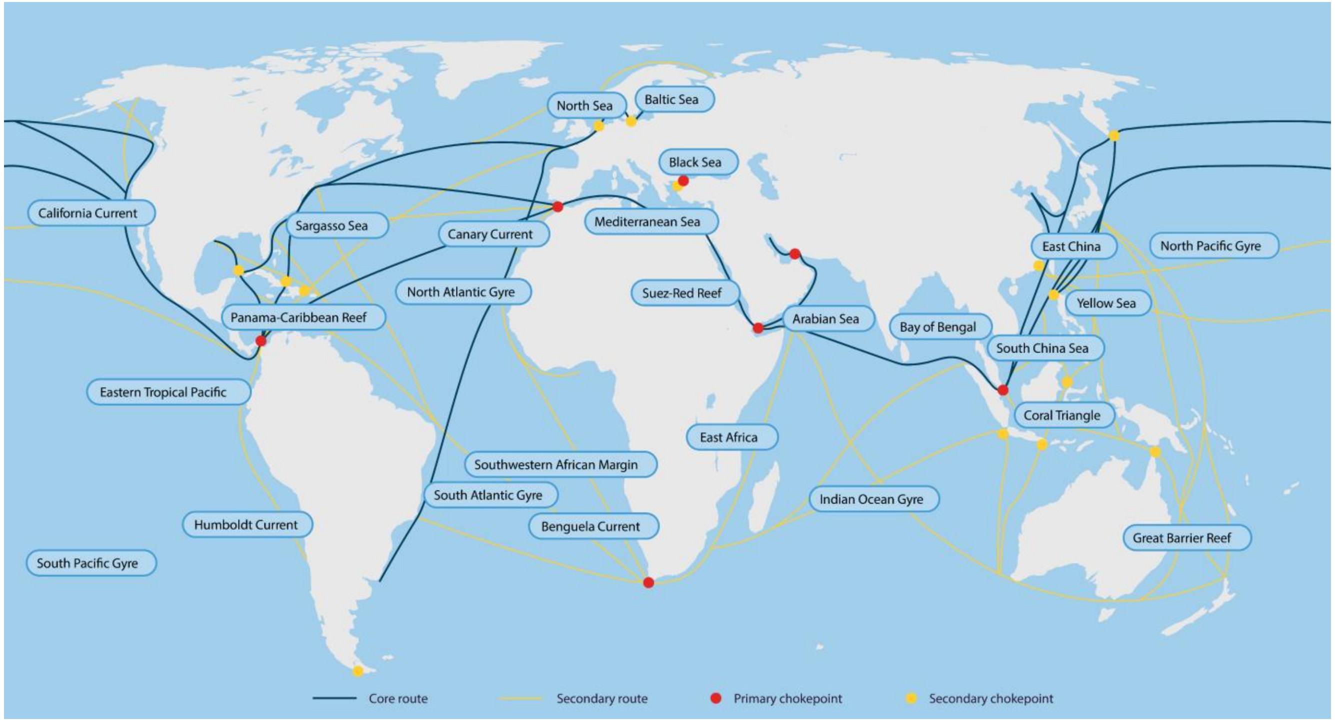
- **NH_3 leakage and releases** across the value chain
- **NH_3 slip** from incomplete combustion
- **NOx** produced during combustion
- **Direct N_2O** from production and engines
- **Indirect N_2O**, formed after NH_3 and NOx are deposited and transformed in natural environments

Source: Gilliam et al. (2026), *Frontiers in Marine Science*


NOx
NH_3
Indirect N_2O
Atmospheric: ~1%
Oxygen-depleted waters: 1–4%
Aerobic waters: <0.1%
of N to N_2O-N
4) Atmospheric transport →
ocean deposition → ecosystem fate
Nr transport
Nr deposition
Marine nitrogen cycle

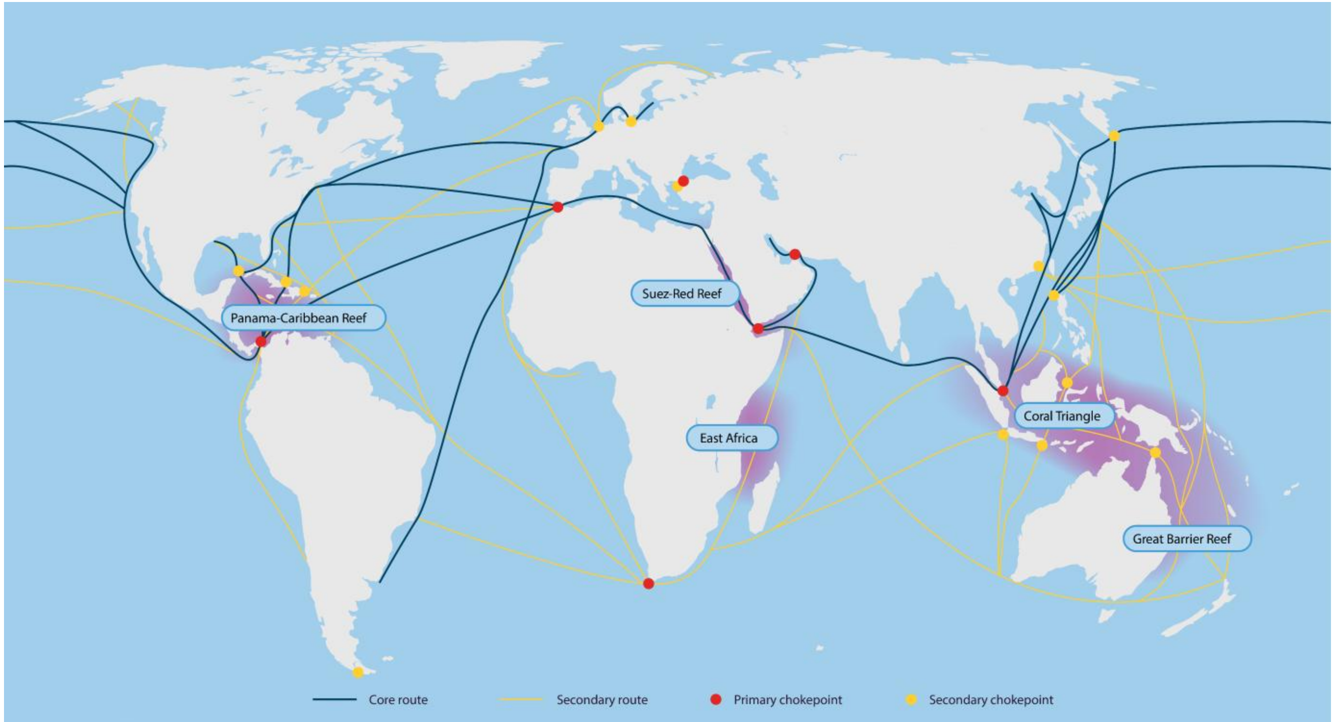
2. Marine ecosystem and climate consequences of Nr

The impacts of deposited Nr vary across marine ecosystems



- The same quantity of deposited Nr can produce very different outcomes depending on where it lands and the characteristics and sensitivity of the receiving marine ecosystem

Coral reefs: Nitrogen enrichment and ecological degradation

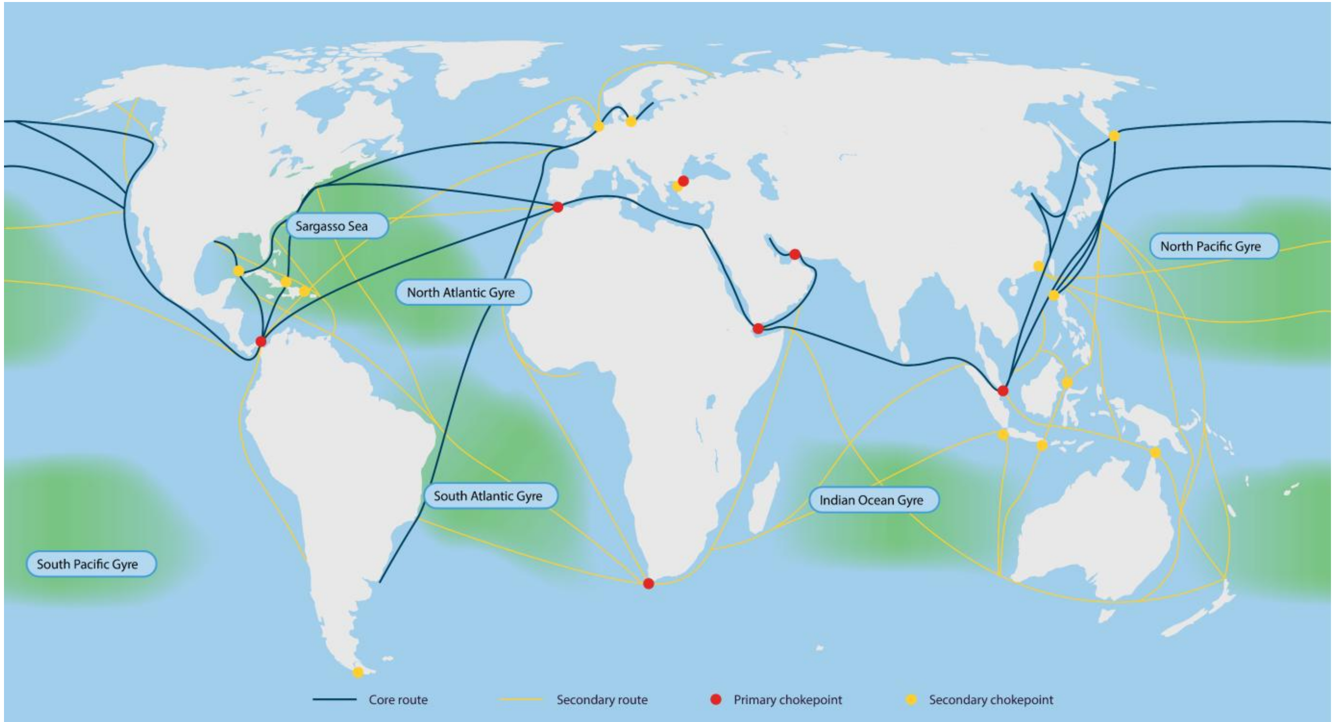


N_2O yield <0.1%*

- Disruption of coral-zooxanthellae symbiosis
- Favoring macroalgae over corals
- Increasing vulnerability to thermal stress (↑ bleaching)

Source: Gilliam et al. (2026), *Frontiers in Marine Science;* * % of deposited nitrogen biogeochemically converted into N_2O

Oligotrophic gyres: N limitation and ecosystem sensitivity

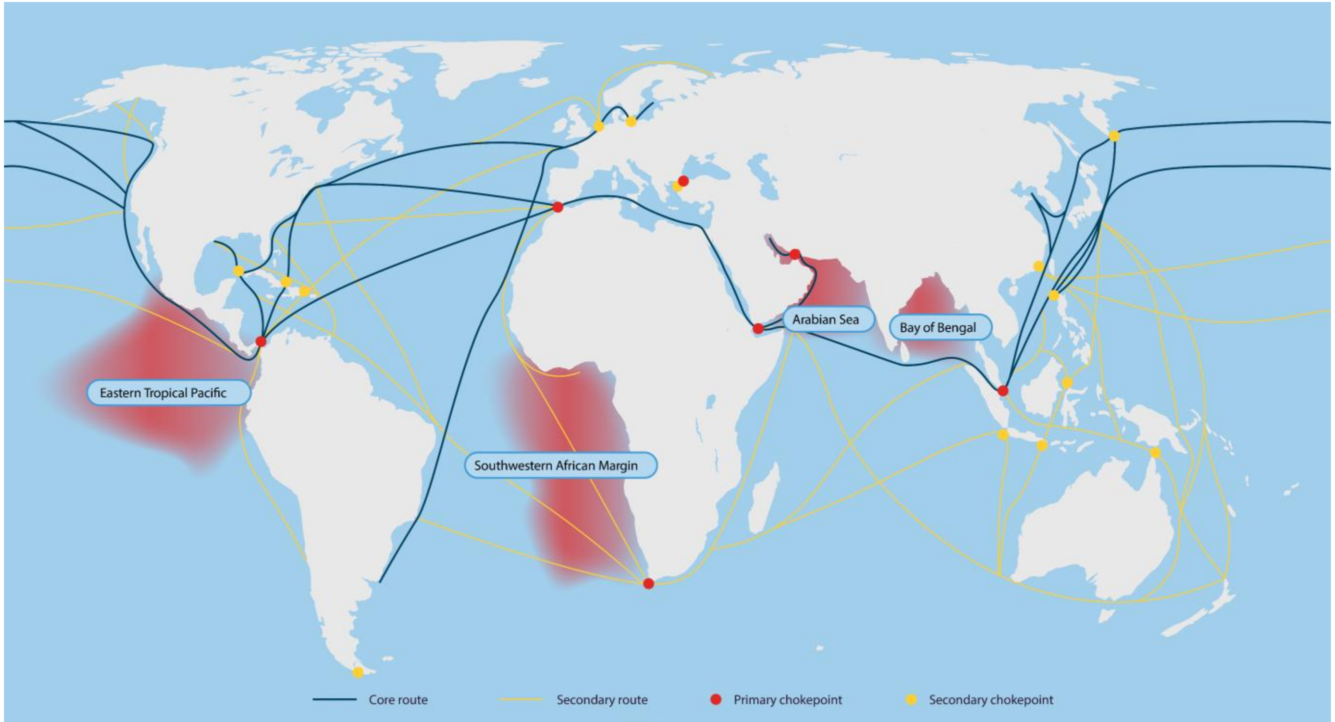


N_2O yield <0.1%*

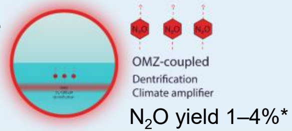
- Increased primary production, disrupting naturally nutrient-limited conditions
- Shifts in phytoplankton communities, affecting net carbon sequestration

Source: Gilliam et al. (2026), *Frontiers in Marine Science;* * % of deposited nitrogen biogeochemically converted into N_2O

Oxygen-minimum zones: indirect N_2O and climate feedback

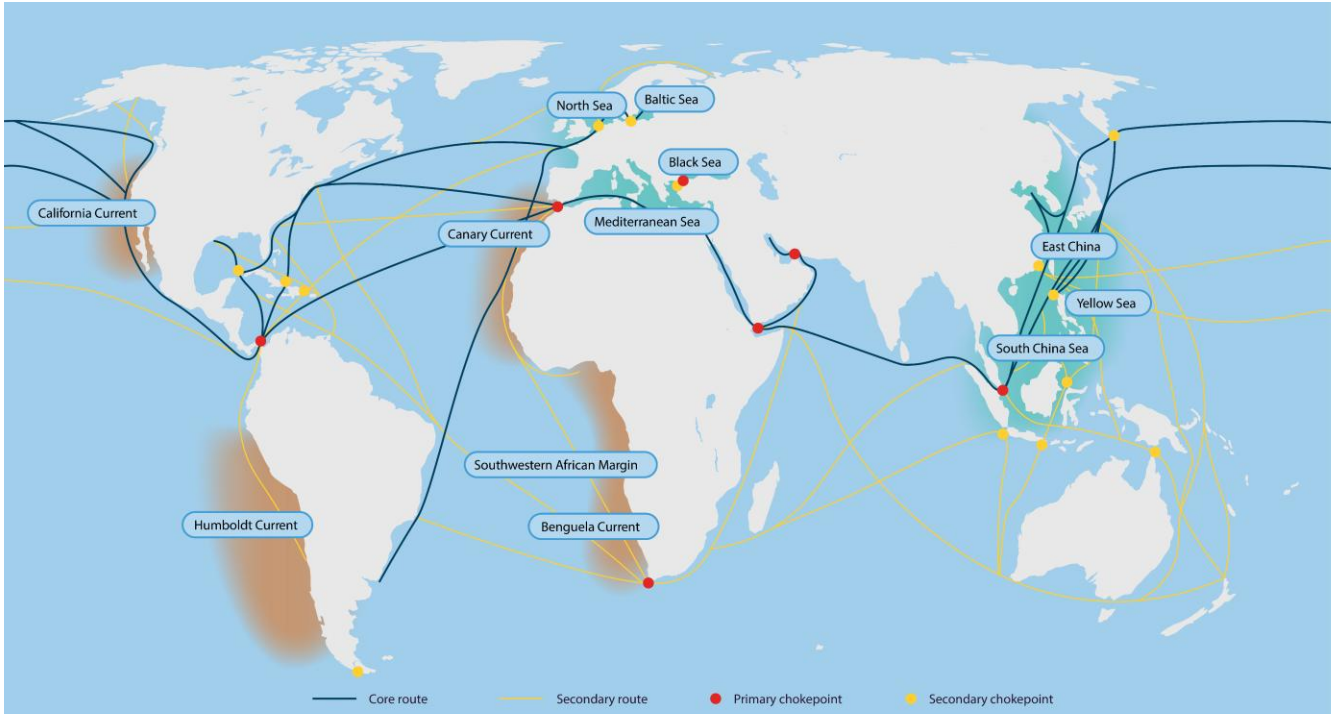


- N_2O formation, amplifying the climate impact of Nr emissions



Source: Gilliam et al. (2026), *Frontiers in Marine Science;* * % of deposited nitrogen biogeochemically converted into N_2O

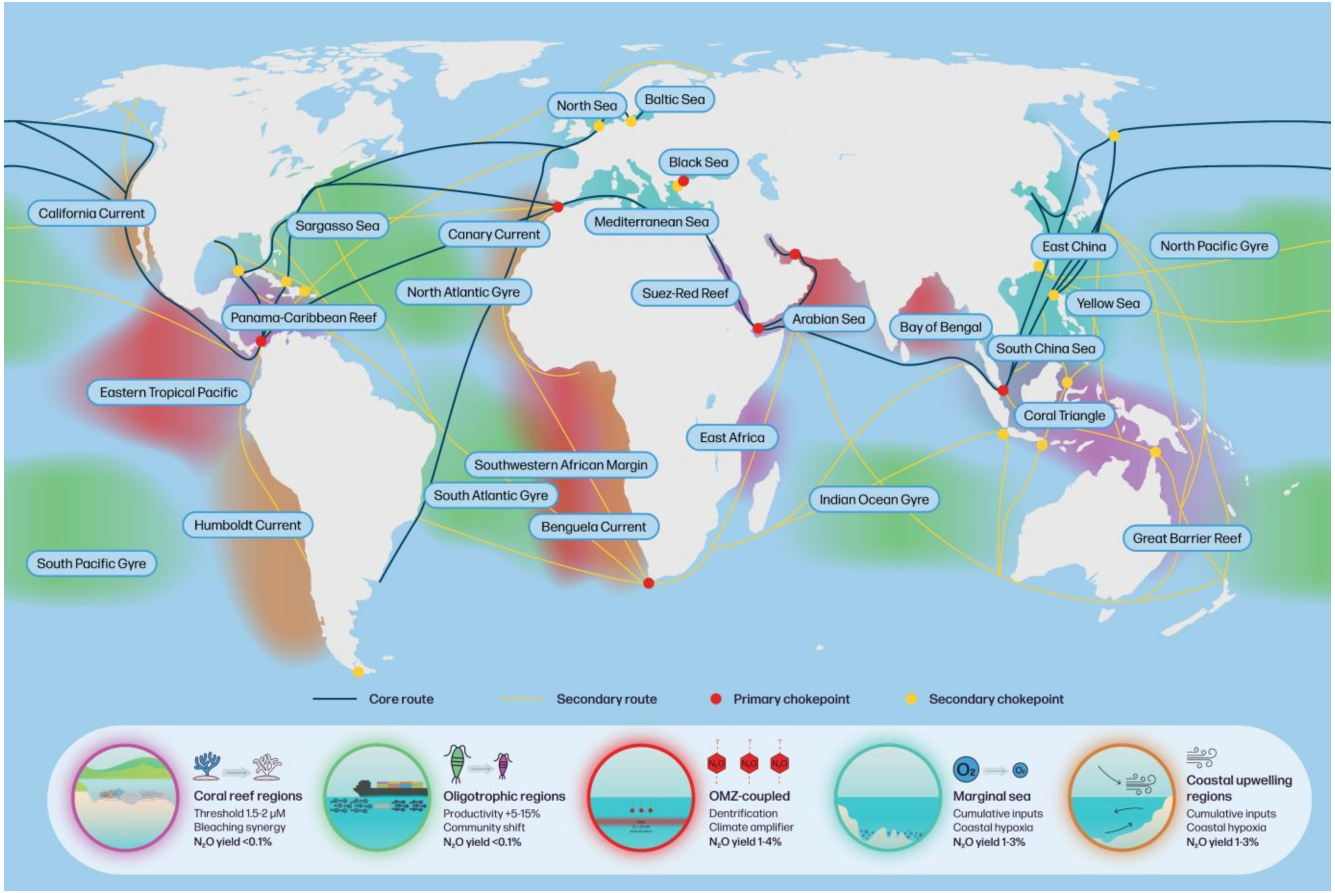
Coastal regions and marginal seas: eutrophication amplification



- Worsened nutrient loads, intensifying eutrophication and oxygen depletion
- Degradation of seagrass meadows and associated ecosystem services

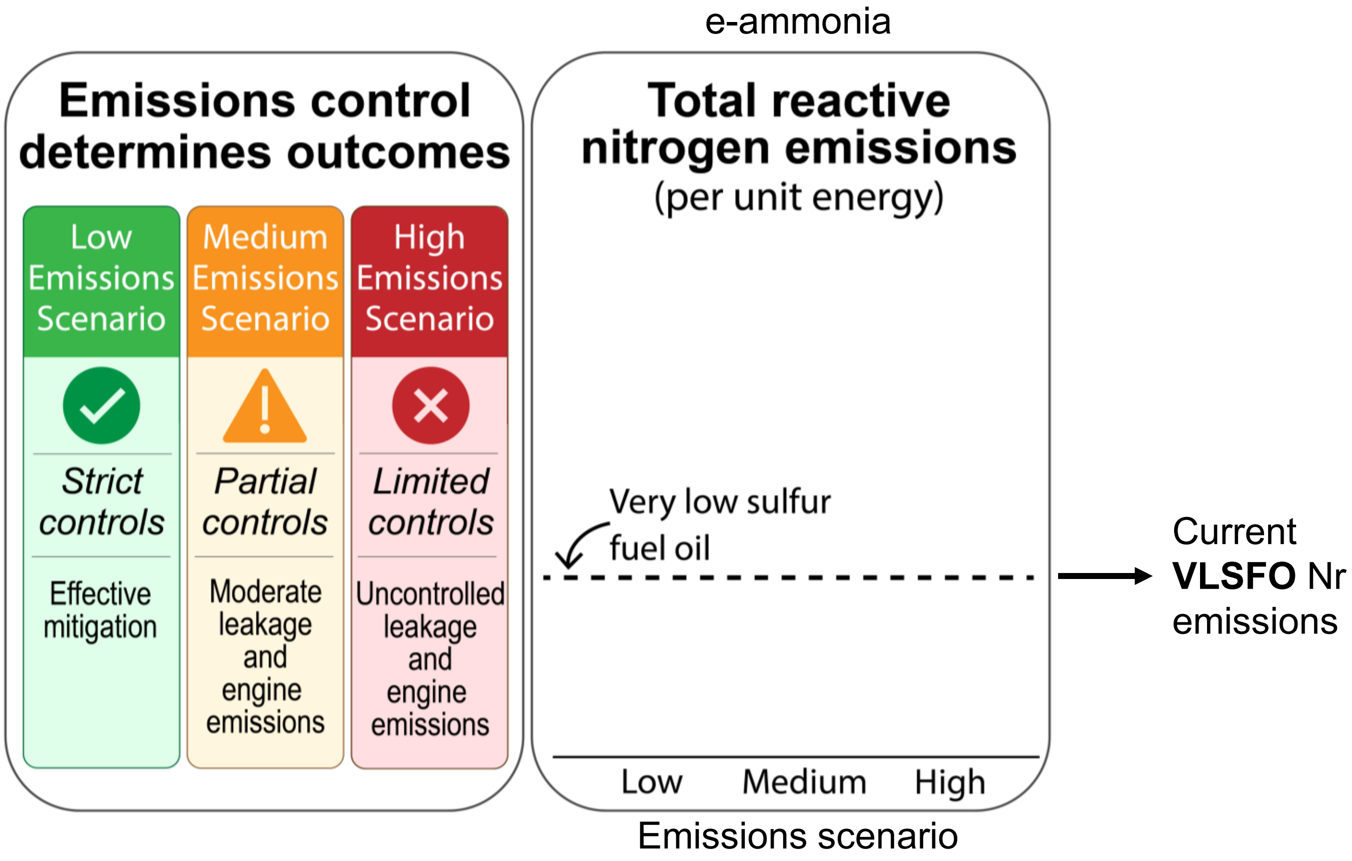
Source: Gilliam et al. (2026), *Frontiers in Marine Science;* * % of deposited nitrogen biogeochemically converted into N_2O

Shipping routes cross ecosystems with different sensitivities



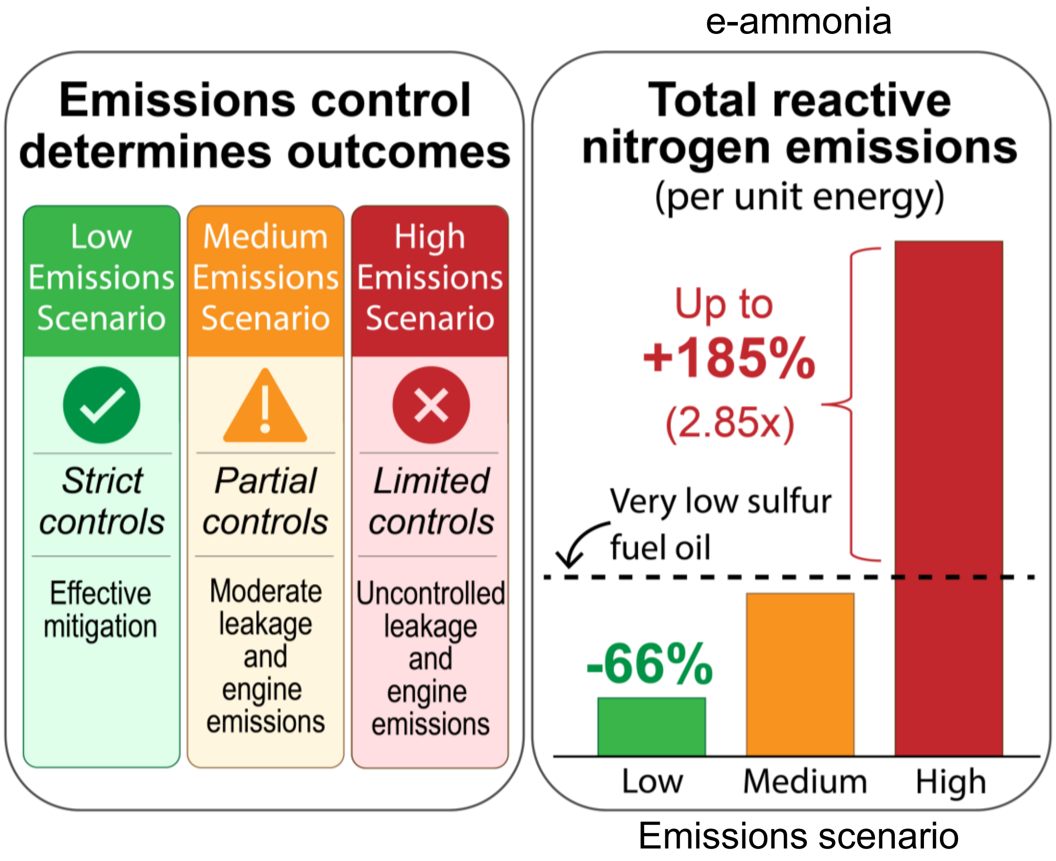
- The same emission rate can produce very different outcomes depending on where the Nr is deposited
- Uncontrolled Nr emissions could threaten regions critical to marine biodiversity and fisheries production

Projected reactive nitrogen (Nr) emissions



Source: Esquivel-Elizondo et al. (2026), *Nature Communications Sustainability*

Projected reactive nitrogen (Nr) emissions



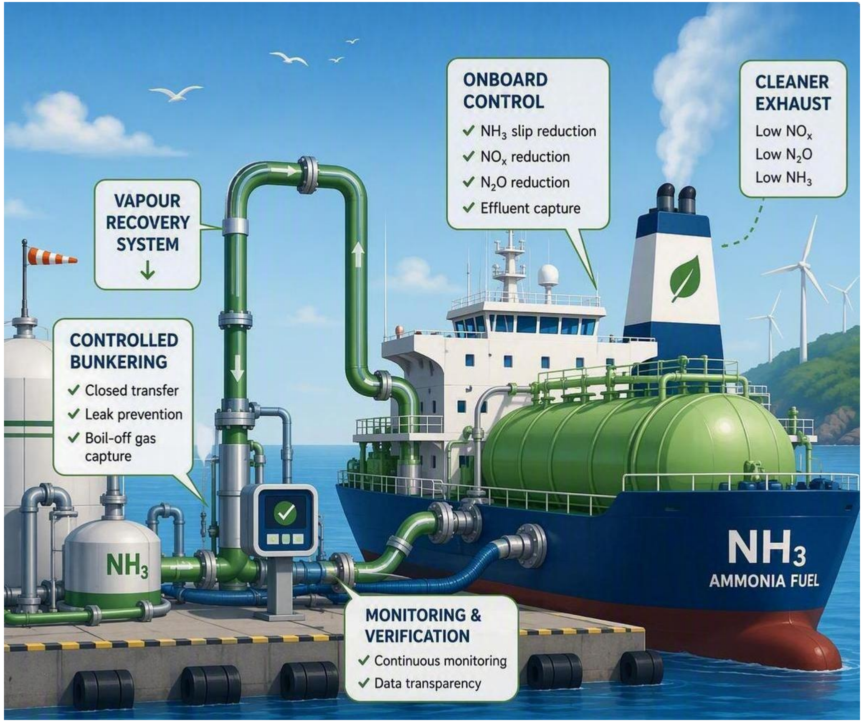
- Total Nr emissions could become substantial within the next 15 to 25 years as ammonia production scales up

  ~0.5–4.4% of the nitrogen supplied to the value chain, depending on emission controls

- The extent of Nr emissions and their environmental impact is determined by the effectiveness of emissions mitigation

3. Emissions control needed

Controls are essential to preserve ammonia's climate and environmental benefits



Prevent
- Use low-emission production
- Minimize leaks and losses

Capture
- Recover and re-use vapors
- Contain and treat nitrogen-containing residuals

Control jointly
- Optimize after-treatment for NH_3, NOx, and N_2O together

Verify
- Monitor emissions and environmental risks
- Report and improve continuously

Key takeaways

Ammonia has a reactive-nitrogen (Nr) footprint across its full value chain

NH_3 leakage and slip, NOx, direct and indirect N_2O, as well as nitrogen-bearing effluent

Nr emissions affect climate and marine ecosystems

Impacts depend on location

Include science-based controls across the full lifecycle

Strong lifecycle controls can preserve ammonia's climate benefits and prevent pollution

Address impacts, not just GHG emissions

Indirect climate warmers (indirect N_2O), Nr discharges to water and effects on ecosystems should be part of the goal

Lifecycle accounting

Stringent emission controls

Attention to marine ecosystem impacts

References and resources

PEER-REVIEWED ARTICLES:

Gilliam L., Kershaw, J., Sartzetakis, S.S., Cabbia Hubatova, M., and Esquivel-Elizondo, S. (2026). Beyond carbon: reactive nitrogen emissions from ammonia as a marine fuel and implications for ocean ecosystems. *Frontiers in Marine Science* 13:1907733

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Esquivel-Elizondo S., Walkowiak, B., Sartzetakis, S., Buma B. (2025). The climate impact of direct and indirect N_2O emissions from the ammonia marine fuel value chain. *Environmental Science & Technology* 59,18, 9037-9048

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BLOGS:

Esquivel-Elizondo and Ocko (2026). Getting alternative fuels right: A science-based blueprint for a sustainable energy transition

Rote and Farrag-Thibault (2025). Quadrupling Sustainable Fuels by 2035? Only If They're Truly Sustainable

Esquivel-Elizondo (2025). Clarifying the environmental impacts of ammonia as a shipping fuel: A call for deeper understanding and effective management

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