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Reducing nitrate loads to the St. Lawrence river could mitigate hypoxia and acidification in its deep estuary and Gulf

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E-mail: david.levesque@dfo-mpo.gc.ca**Keywords:** eutrophication, hypoxia, St. Lawrence estuary, coupled physical-biogeochemical modelling, acidification, nitrogen managementSupplementary material for this article is available [online](#)

Abstract

Hypoxia in marine systems is expanding worldwide due to anthropogenic activities. Deep waters of the St. Lawrence Estuary and Gulf are rapidly deoxygenating ($\sim 1 \text{ mmol O}_2 \text{ m}^{-3} \text{ y}^{-1}$), driven by changes in Atlantic water-mass intrusion and nutrient-fueled remineralization, and are simultaneously acidifying ($\sim 0.004 \text{ pH unit y}^{-1}$). These changes alter biogeochemical cycles and degrade habitats, causing biotic and economic consequences. Using a coupled physical-biogeochemical model, we tested whether watershed-scale nitrate reductions could mitigate deep-water deoxygenation and carbonate-system degradation. Three nitrate-reduction scenarios reduced riverine St. Lawrence River nitrate loads by about 11%, 30%, and 50% (-2.8 , -7.5 , and $-11.7 \text{ mmol N m}^{-3}$, respectively). Relative to the baseline simulation, these scenarios increased dissolved oxygen concentrations (DO) ($+1.6$, $+4.3$, and $+6.7 \text{ mmol O}_2 \text{ m}^{-3}$), pH ($+0.004$, $+0.010$, and $+0.016$), and aragonite saturation state (Ω_{arag}) ($+0.003$, $+0.009$, and $+0.015$) in the deep Laurentian Channel ($\geq 175 \text{ m}$). The volume of deep waters with DO saturation $< 30\%$ decreased by 3%, 8%, and 13% (-27 , -75 , -122 km^3), while volumes with pH < 7.65 declined by 1.0%, 2.8%, and 4.5% (-22 , -60 , -96 km^3). Severely corrosive waters ($\Omega_{\text{arag}} < 0.6$) dropped by 1.4%, 3.7%, and 5.9% (-26 , -71 , -112 km^3). Over 2014–2024, modelled improvements exceeded small interannual variability but remained within seasonal amplitudes of deep DO concentrations ($\sim 11 \text{ mmol O}_2 \text{ m}^{-3}$) and pH (~ 0.015 units), nevertheless pointing to a detectable management signal. Although nutrient-driven improvements remained smaller than climate-forced trends, modelled nitrate load reductions could offset $\sim 56\%$ and 80% of recent observed oxygen and pH declines, respectively, while reducing hypoxic and acidified (pH and Ω_{arag}) water volumes. These findings provide quantitative evidence that watershed-scale nitrogen mitigation, through improved agricultural practices and wastewater nitrogen removal, which necessitates cooperation across jurisdictions, can alleviate hypoxia and acidification in deep coastal ecosystems, making nutrient management an essential complement to climate adaptation strategies.

1. Introduction

Eutrophication and its consequences have become one of the most pressing threats to aquatic ecosystems, with >500 hypoxic zones documented in the global ocean (Rabalais *et al* 2014, Malone and Newton 2020). This process is primarily driven by anthropogenic increases in nitrogen (N) and phosphorus (P) inputs (Le Moal *et al* 2019, Wurtsbaugh *et al* 2019). Nutrient enrichment stimulates primary production, and the exported organic matter is remineralised by aerobic bacteria consuming dissolved oxygen (DO), leading to hypoxia at depth (Diaz and Rosenberg 2008, Rabalais *et al* 2014). Respiration releases carbon dioxide (CO₂), increasing dissolved inorganic carbon (DIC) concentrations which reduces pH and saturation state of calcium carbonate minerals such as aragonite (Ω_{arag}) (Wallace *et al* 2014, Cai *et al* 2021). Consequently, deoxygenation and acidification co-occur in coastal systems, degrading habitats, altering biogeochemical cycles, and reducing ecological and economic value of ecosystems (Gobler and Baumann 2016).

Effective eutrophication control requires targeting the nutrient that most strongly limits primary production. In freshwater systems, P typically limits phytoplankton growth (Higgins *et al* 2017) and P-reduction measures have restored many lakes and rivers (Schindler *et al* 2016). In contrast, N commonly limits productivity in coastal and marine environments, making N reduction the primary management focus (Howarth and Marino 2006). Large watersheds that span fresh-to-marine waters present particular governance challenges: upstream freshwater policies may regulate P while downstream impacts are driven by N. The St. Lawrence system exemplifies this duality: P control has been central to restoration efforts in the Great Lakes (Watson *et al* 2016) and the St. Lawrence River (Twiss *et al* 2022) whereas N drives eutrophication in the Estuary and Gulf (Hudon *et al* 2017). Observations and experiments in the St. Lawrence confirmed phytoplankton responses to nitrate enrichment (Paradis-Hautcoeur *et al* 2023), with N:P stoichiometry shifting from P-limitation in upstream freshwaters to N-limitation in downstream marine waters (Villeneuve 2020).

The St. Lawrence system encompasses the second largest freshwater reserve on Earth and drains a watershed of ~ 1.75 million km² (Lamberti *et al* 2023). The Estuary and Gulf of St. Lawrence (EGSL) rank among North America's most productive marine ecosystems, sustaining major fisheries, marine mammal populations, and tourism (Working Group on the State of the St. Lawrence Monitoring 2024). However, EGSL demersal waters are subject to multiple stressors, including deoxygenation (Gilbert *et al* 2005) and acidification (Mucci *et al* 2011) driven by changes in the proportion of the different water masses (North Atlantic Central Waters [NACW] and

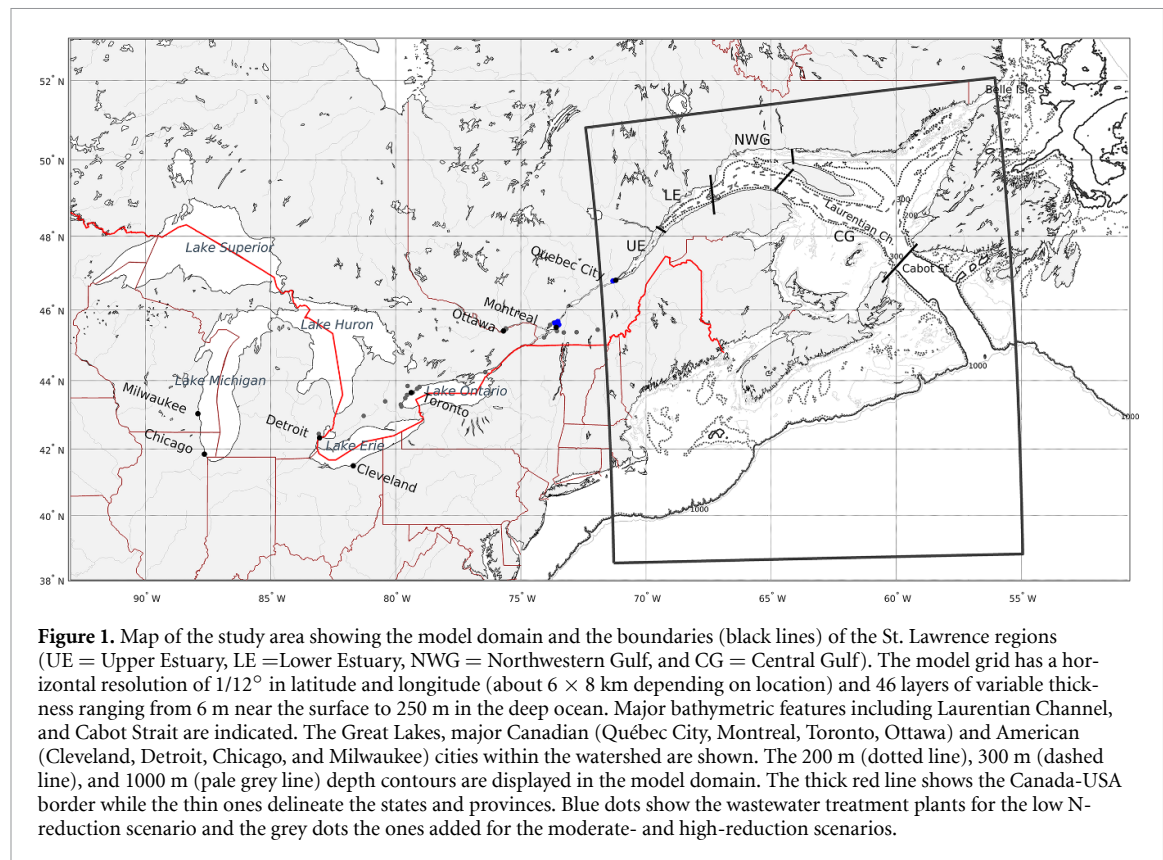
Labrador Current) entering the Laurentian Channel, where increased inputs from NACW leads to warmer deep waters with more nutrients and reduced oxygen concentrations (Jutras *et al* 2023). This climate-related pressure leading to habitat degradation for marine species (Chabot and Claireaux 2008, Dupont-Prinet *et al* 2013, Brown-Vuillemin *et al* 2022) is compounded by riverine nutrients exported from one of North America's most densely populated (>60 million people) and agriculturally intensive watersheds (Hudon *et al* 2017, Lévesque *et al* 2023). Organic matter derived from these nutrients is remineralised in the deep, poorly ventilated layer of the Laurentian Channel, exacerbating hypoxia and acidification (Hudon *et al* 2017, Lavoie *et al* 2021, Lévesque *et al* 2024). Although large-scale ocean circulation changes exert a dominant influence on deep-water oxygen trends (Jutras *et al* 2020, Rousseau *et al* 2025), watershed-derived nutrient reduction remains the only direct regional management lever.

In this study, we tested whether substantial reductions in nitrate inputs from the St. Lawrence River, originating from agriculture and wastewater treatment plants (WWTPs), could mitigate deoxygenation and acidification in the deep waters of the EGSL. Using a validated coupled physical-biogeochemical model that resolves N cycling, DO dynamics, and carbonate system processes (Lavoie *et al* 2021), we simulated a baseline and three increasingly stringent nitrate-reduction scenarios. We quantified changes in DO concentrations, pH_t (total scale), and Ω_{arag} , as well as reductions in water volumes crossing ecologically relevant thresholds for hypoxia (<30% DO saturation) and acidification (pH < 7.65 and Ω_{arag} < 0.6) to assess the potential for habitat rehabilitation.

2. Methods

2.1. Study area

The system begins with the Great Lakes (25 700–82 170 km²) (figure 1), which deliver low total phosphorous (~ 0.484 mmol P m⁻³) but high total nitrogen (~ 40.0 mmol N m⁻³) to the St. Lawrence River (mean annual discharge of $\sim 12\,000$ m³ s⁻¹ near Québec City), yielding high molar N:P ratios (82.6) at the River-Estuary transition zone (Hudon *et al* 2017). Approximately 50 WWTPs along the River contribute $\sim 6\%$ of the total annual N load, estimated at $\sim 270\,000$ t N y⁻¹ (Hudon *et al* 2017). The Upper Estuary (~ 30 m deep, ~ 20 km wide) extends nearly 200 km, from Québec City (salinity front) to the Saguenay Fjord. Strong tidal mixing (4–6 m tidal amplitudes) and turbidity constrain phytoplankton growth primarily via light limitations (Painchaud and Therriault 1989), reducing local responses to nutrient abatement and promoting their downstream export. Downstream of the Saguenay Fjord mouth, the estuary widens (20–50 km) into the more marine



Lower St. Lawrence Estuary (LSLE), much deeper than the Upper Estuary, reaching ~ 350 m in the Laurentian Channel. The latter stretches ~ 800 km through the Gulf, and reaches ~ 500 m near Cabot Strait (figure 1). On average, the EGSL has estuarine circulation, with a seaward flow in the upper layer (0–40 m) and deep landward inflow. Shallow sills (40 – 70 m), tidal upwelling and strong mixing at the Laurentian Channel head (Therriault and Lacroix 1976, Greisman and Ingram 1977, Saucier and Chassé 2000) create ecologically relevant hydrodynamic processes (Therriault and Levasseur 1985, Simard and Lavoie 1999, Cyr et al 2015). In summer, the water column is subdivided in three layers: the surface mixed layer, a winter-formed cold intermediate layer (40–140 m) persisting until late autumn (Galbraith 2006) and a nutrient-rich deep layer (≥ 175 m) consisting mostly of Atlantic water entering at Cabot Strait. This inflow combines cold Labrador Current water ($\sim 34\%$) and warmer NACW ($\sim 66\%$), but may have reached 100% NACW in 2021 before declining slightly thereafter (Claret et al 2018, Jutras et al 2023, Galbraith et al 2025). The LSLLE is N-limited, with molar N:P ratios of 8.5 ± 0.4 in surface waters and 11.2 ± 0.5 in deep waters over 1999–2020 (Blais et al 2025). In the deep layer, nitrate concentrations increase by ~ 2 mmol N m $^{-3}$ (Coote and Yeats 1979) between Cabot Strait and the head of the Laurentian Channel, accompanied by decreases in DO concentrations (147–61 mmol O $_2$ m $^{-3}$) (Blais et al 2025), p*H*_T (~ 7.8 to

~ 7.5), Ω_{calc} (~ 1.8 – 0.7), and Ω_{arag} (~ 1.25 to ~ 0.5) (Mucci et al 2011, Gibb et al 2023, Lizotte et al 2026) (figures 2 and S1).

2.2. Numerical model

We used the coupled physical-biogeochemical Gulf of St. Lawrence model described and validated by Lavoie et al (2021) (see domain in figure 1). The hydrodynamic component uses the Nucleus for European Modelling of the Ocean system and resolves temperature, salinity, circulation, and sea ice. The biogeochemical module simulates the herbivorous export food web and a microbial nutrient recycling loop and comprises 11 state variables: nitrate, ammonium, dissolved organic nitrogen, particulate organic nitrogen (PON), DIC, total alkalinity (TA), DO, large phytoplankton, diatoms and small phytoplankton, mesozooplankton, and microzooplankton. Nitrogen transformations (primary production, grazing, remineralization, nitrification) are stoichiometrically coupled to oxygen and carbon cycling, enabling mechanistic DO and DIC simulations. Since Lavoie et al (2021), a sediment box has been added to the model to include remineralization of settling organic matter at a rate of 0.05 d $^{-1}$. Additionally, 3% of the organic matter is permanently buried, improving fidelity to observed deep-water DIC accumulation and oxygen consumption. The simulation was run from 01/05/2005 to 31/12/2024, but the analyses focus on 2014–2024 to allow deep-layer chemistry to approach equilibrium.

Simulated DO reflects the balance among photo-synthetic oxygen production, respiration, remineralization, nitrification, and air–sea exchange, while DIC reflects biological processes and CO₂ exchange, and TA is modified by nitrogen cycling. Seawater pH_t and Ω_{arag} were calculated from simulated TA, DIC, temperature, salinity and sea pressure using the seacarb R package (Gattuso *et al* (2024)). Dissociation constants (k_1 , k_2) followed Lueker *et al* (2000), except when temperature fell outside 2 °C–35 °C or salinity outside 19–43, in which case Waters *et al* (2014) was applied. Default settings of function carb were applied (see Gattuso *et al* (2024)), except for total boron concentration, which followed Lee *et al* (2010). The model reproduced observed mean spatial patterns of DO, pH_t, and Ω_{arag} across the EGSL, both horizontally and vertically (figures 2 and S2) (Gibb *et al* 2023), including the lowest values at depth near the Laurentian Channel head.

2.3. Scenarios

A baseline simulation (134 000 t N y^{−1} nitrate load, Hudon *et al* 2017) was compared to three N-reduction scenarios (low, moderate, high) applied to the monthly nitrate climatology at the western open boundary of the model (table 1). The low-reduction scenario (−2.77 mmol N m^{−3}, ~11% N-load decrease) combines ~15% lower agricultural nitrate concentrations (−1.5 mmol N m^{−3}) from a 15% reduction in manure and fertiliser N inputs under Québec's Plan d'agriculture durable 2020–2030 (table S1), with N removal at the four largest Québec WWTPs (>170 000 m³ d^{−1}) upstream of the model boundary contributing an additional −1.27 mmol N m^{−3}. The moderate reduction (−7.48 mmol N m^{−3}, ~30% reduction of the baseline load) combines ~30% agricultural reduction with N removal at additional large Ontario and Québec WWTPs (table 1). The high reduction halves nitrate inputs (−11.7 mmol N m^{−3}), an ambitious benchmark used in international frameworks (OSPAR 2023, HELCOM 2025). Total dissolved nitrogen from agricultural lands, mainly nitrate (~85%) (Gangbazo *et al* 1997, Gangbazo and Babin 2000, Patoine 2010), and total nitrogen from WWTPs, primarily dissolved organic nitrogen (~59%) and ammonia (~40%) (Hudon *et al* 2017) were assumed to largely convert to nitrate before reaching Québec City. This simplifies complex transformation pathways but is reasonable for load estimation. Because some nitrogen is not fully transformed into nitrate during transport, this fraction could represent additional agricultural and WWTP N reduction from the Ontario and U.S. Great Lakes watershed segments. Reductions were applied evenly year-round. Seasonal targeting (e.g. spring freshet) may improve N-mitigation efficiency, but is beyond the scope of this paper.

2.4. Indicators of hypoxia and acidification

Changes in ecosystem responses were quantified with six indicators (table 2). Mean values were calculated for deep waters (≥175 m) whereas hypoxic and acidified (low pH_t and Ω_{arag}) volumes were computed for waters ≥100 m to exclude fresh surface waters with naturally low pH_t and calcium carbonate saturation (figure 2). Hypoxia was characterised using mean deep-water DO concentrations (mmol O₂ m^{−3}) and the volume of water with DO saturation <30%, an avoidance threshold for Atlantic cod (Chabot and Claireaux 2008). Acidification was characterised using mean deep-water pH_t, and Ω_{arag} , together with water volume with pH_t <7.65 and Ω_{arag} <0.6. These thresholds represent strongly acidified conditions within the EGSL (figure 2) and are consistent with some of the lowest values reported in 2017 by Gibb *et al* (2023). The saturation state of seawater with respect to calcium carbonate (Ω_{arag} < 0.6) directly influences marine calcifying organisms (Doney *et al* 2009, Cai *et al* 2021). Sensitivity analyses showed that higher threshold values enlarge hypoxic and acidified volumes and reduce relative improvement. The selected values emphasise the most hypoxic and acidified habitats and yield conservative estimates of potential remediation.

3. Results and discussion

3.1. System response to nitrate reduction

Nitrate reduction in the St. Lawrence River watershed improved all indicator values across scenarios (table 3). In the LSLE, mean deep-water (≥175 m) DO rose by +1.6, +4.3, and +6.7 mmol m^{−3} under the low, moderate, and high N-reduction scenarios, respectively, relative to baseline. Mean pH_t increased by +0.004, +0.010, and +0.016, while Ω_{arag} rose by +0.003, +0.009, and +0.015. These increases expanded habitat volume substantially (table 3) for oxygen- and carbonate-sensitive taxa (Ekau *et al* 2010, Gilly *et al* 2013, Gallo and Levin 2016). Volumes (≥100 m) of hypoxic waters (DO sat < 30%) decreased by −27 km³ (3%), −75 km³ (8%), and −122 km³ (13%); of acidified waters (pH_t <7.65) by −22 km³ (1.0%) −60 km³ (2.8%), and −96 km³ (4.5%); and, of corrosive waters (Ω_{arag} <0.6) by −26 km³ (1.4%), −71 km³ (3.7%), and −112 km³ (5.9%), respectively. Improvements mostly fell near the Laurentian Channel head, first in the LSLE and then extending into the northwestern Gulf, consistent with Lavoie *et al* (2021), which showed increased deep DO concentrations in the same area without primary production.

The magnitude of habitat recovery increased linearly with incremental nitrate reductions (figure 3). Despite substantial interannual variability in intercepts, the slopes of the relationships between nitrate reductions and hypoxia and acidification indicators

Table 1. Nitrate concentrations and total load reductions in the St. Lawrence watershed applied at the western open boundary of the model near Québec City (QC) under the baseline climatology and three nitrogen reduction scenarios.

Scenario	Agricultural nitrogen reduction	Agricultural nitrogen load reduction (t N y ⁻¹)	WWTP nitrogen reduction	WWTP nitrogen load reduction (t N y ⁻¹)	Mean total nitrate conc. at QC (mmol N m ⁻³)	Total load reduction (t N y ⁻¹) ^a	% Load reduction
Baseline	0%	0	Current	0	23.4 ^b	0	0%
Low	15% (1.5 mmol m ⁻³)	8 000	Nitrogen removal at 4 largest Québec WWTPs upstream model boundary (1.27 mmol m ⁻³) ^c	6 763	20.6	14 763	~11%
Moderate	30% (3.0 mmol m ⁻³)	16 000	Nitrogen removal at 24 large Ontario & Québec WWTPs upstream model boundary (4.48 mmol m ⁻³) ^d	23 930	15.9	39 930	~30%
High	50% (5.0 mmol m ⁻³)	26 900	Additional reductions totalizing 6.7 mmol m ⁻³	39 650	11.7	66 550	~50%

^a Reductions are applied to the total nitrite-nitrate baseline river load of 134 000 t N y⁻¹ (Hudon *et al* 2017) and distributed evenly throughout the year.

^b Mean annual nitrate concentration for 1995–2011 period (Hudon *et al* 2017).

^c Corresponding to four wastewater treatment plants (WWTPs) located upstream of the model boundary: Laval (La Pinière), Longueuil, Montreal (J.-R. Marcotte), Québec (West).

^d Includes the four Québec stations listed under the low reduction scenario, plus additional facilities: Gatineau, Laval (Fabreville), St-Jean-sur-Richelieu, Laprairie, Granby, Salaberry-de-Valleyfield, Sherbrooke; Toronto (Ashbridges Bay), Toronto (Humber), Toronto (Highland Creek), Peel (G.E. Booth), Durham (Duffin Creek), Hamilton (Woodward Avenue), Peel (Clarkson), Windsor (Lou Romano), London (Greenway), Ottawa (Robert O. Pickard), Burlington (Skyway), Kitchener, Kingston (Ravensview). The WWTP nitrogen reduction of 4.48 mmol m⁻³ is distributed as follows: 1.51 mmol m⁻³ for Québec and 2.97 mmol m⁻³ for Ontario.

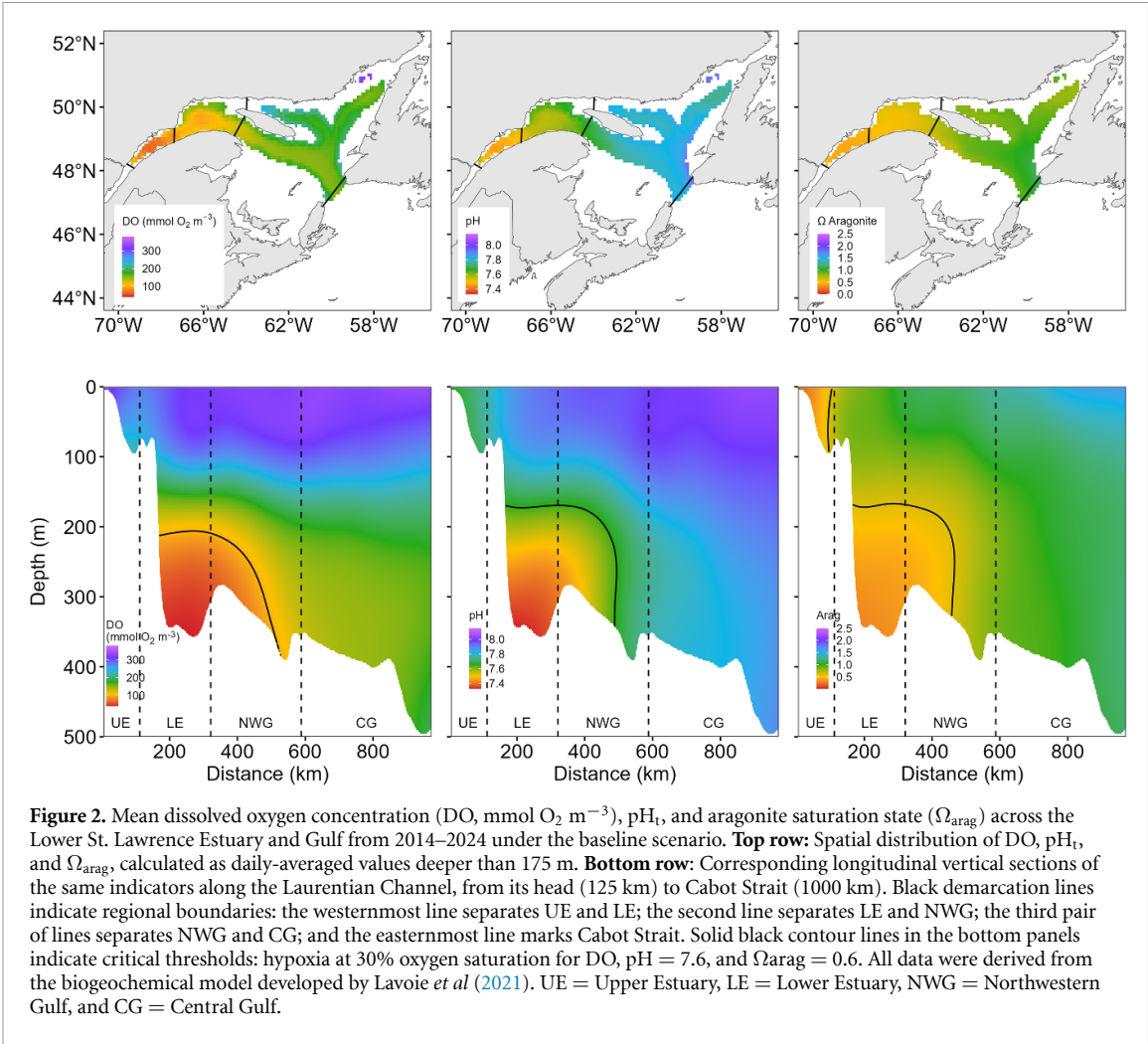


Figure 2. Mean dissolved oxygen concentration (DO, mmol O₂ m⁻³), pH_t, and aragonite saturation state (Ω_{arag}) across the Lower St. Lawrence Estuary and Gulf from 2014–2024 under the baseline scenario. **Top row:** Spatial distribution of DO, pH_t, and Ω_{arag} calculated as daily-averaged values deeper than 175 m. **Bottom row:** Corresponding longitudinal vertical sections of the same indicators along the Laurentian Channel, from its head (125 km) to Cabot Strait (1000 km). Black demarcation lines indicate regional boundaries: the westernmost line separates UE and LE; the second line separates LE and NWG; the third pair of lines separates NWG and CG; and the easternmost line marks Cabot Strait. Solid black contour lines in the bottom panels indicate critical thresholds: hypoxia at 30% oxygen saturation for DO, pH = 7.6, and Ω_{arag} = 0.6. All data were derived from the biogeochemical model developed by Lavoie *et al* (2021). UE = Upper Estuary, LE = Lower Estuary, NWG = Northwestern Gulf, and CG = Central Gulf.

Table 2. Selected indicators of hypoxia and acidification.

Value at depth ≥ 175 m		Water volume (km ³)
Hypoxia		
DO (mmol O ₂ m ⁻³)	Concentration	DO saturation <30%
DO saturation (%)		
Acidification		
pH	pH _t	pH _t < 7.65 at depth ≥ 100 m
Aragonite	Saturation state	Saturation state <0.6 at depth ≥ 100 m

Table 3. Annual means of daily hypoxia and acidification indicators under baseline and N-reduction scenarios (2014–2024). Values are reported as mean $\pm$ SD across years. Deep-water metrics refer to the Lower Estuary at depth ≥ 175 m; volume metrics represent Laurentian Channel waters deeper than 100 m.

Scenario	Deep-water metrics			Volume metrics		
	DO (mmol O ₂ m ⁻³)	pH	Ω_{arag}	DO <30% (km ³)	pH < 7.65 (km ³)	Ω_{arag} < 0.6 (km ³)
Baseline	75.5 $\pm$ 6.8 ^a	7.479 $\pm$ 0.019 ^a	0.428 $\pm$ 0.019 ^a	941 $\pm$ 172 ^a	2134 $\pm$ 182 ^a	1901 $\pm$ 237 ^a
Low	77.1 $\pm$ 6.6 ^b	7.483 $\pm$ 0.019 ^b	0.431 $\pm$ 0.019 ^b	914 $\pm$ 175 ^{ab}	2112 $\pm$ 181 ^b	1875 $\pm$ 238 ^{ab}
Moderate	79.8 $\pm$ 6.3 ^c	7.489 $\pm$ 0.018 ^c	0.437 $\pm$ 0.018 ^c	866 $\pm$ 184 ^c	2074 $\pm$ 179 ^c	1830 $\pm$ 239 ^c
High	82.2 $\pm$ 6.0 ^d	7.495 $\pm$ 0.018 ^d	0.443 $\pm$ 0.018 ^d	819 $\pm$ 195 ^d	2038 $\pm$ 178 ^d	1789 $\pm$ 241 ^d

Linear mixed-effect models were applied (scenarios as fixed effect; years as random intercept, $n = 44$), followed by Holm-adjusted multiple comparisons. Different superscript letters indicate groups that differ significantly at $\alpha = 0.05$.

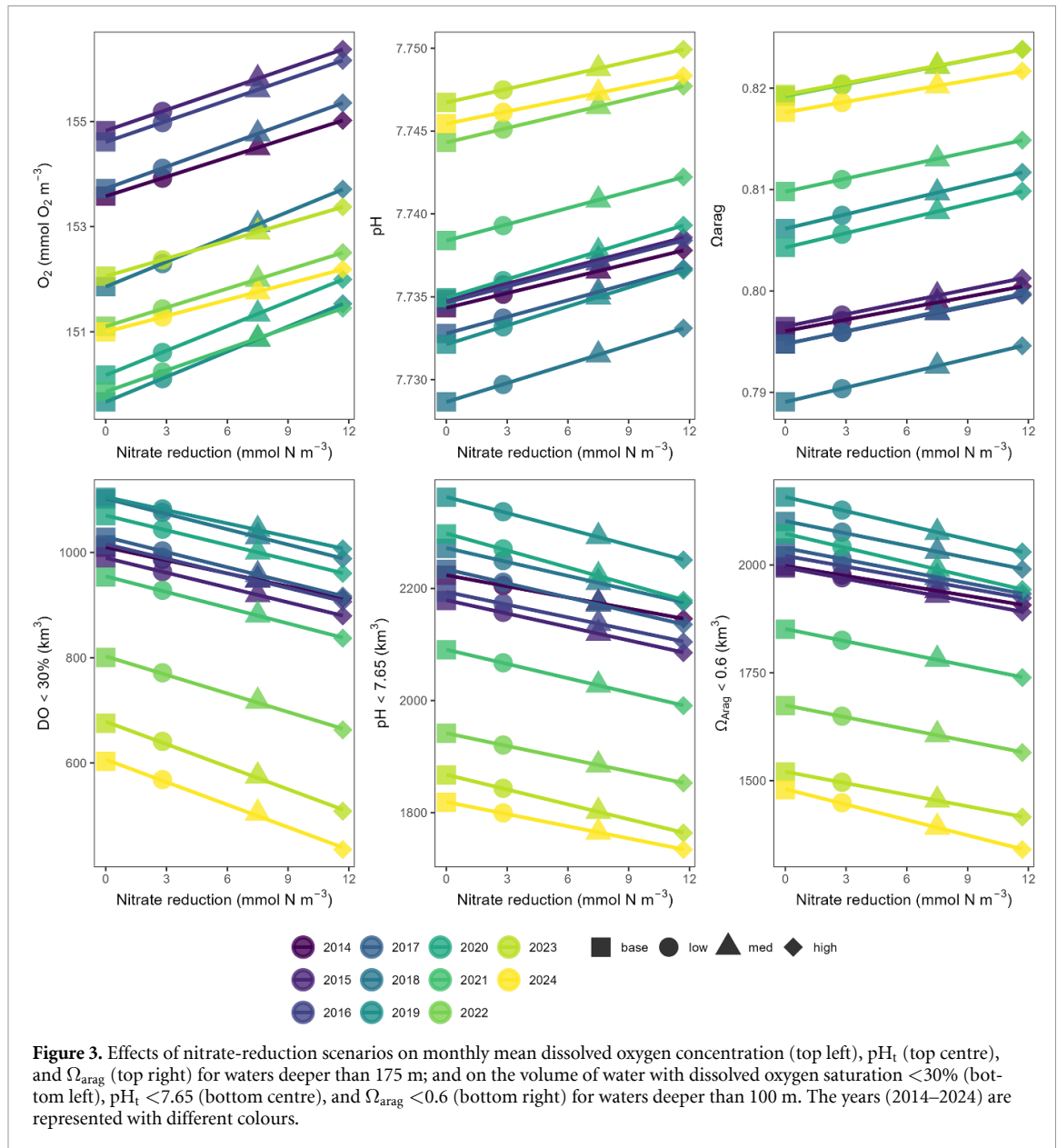


Figure 3. Effects of nitrate-reduction scenarios on monthly mean dissolved oxygen concentration (top left), pH_t (top centre), and Ω_{arag} (top right) for waters deeper than 175 m; and on the volume of water with dissolved oxygen saturation <30% (bottom left), pH_t <7.65 (bottom centre), and Ω_{arag} <0.6 (bottom right) for waters deeper than 100 m. The years (2014–2024) are represented with different colours.

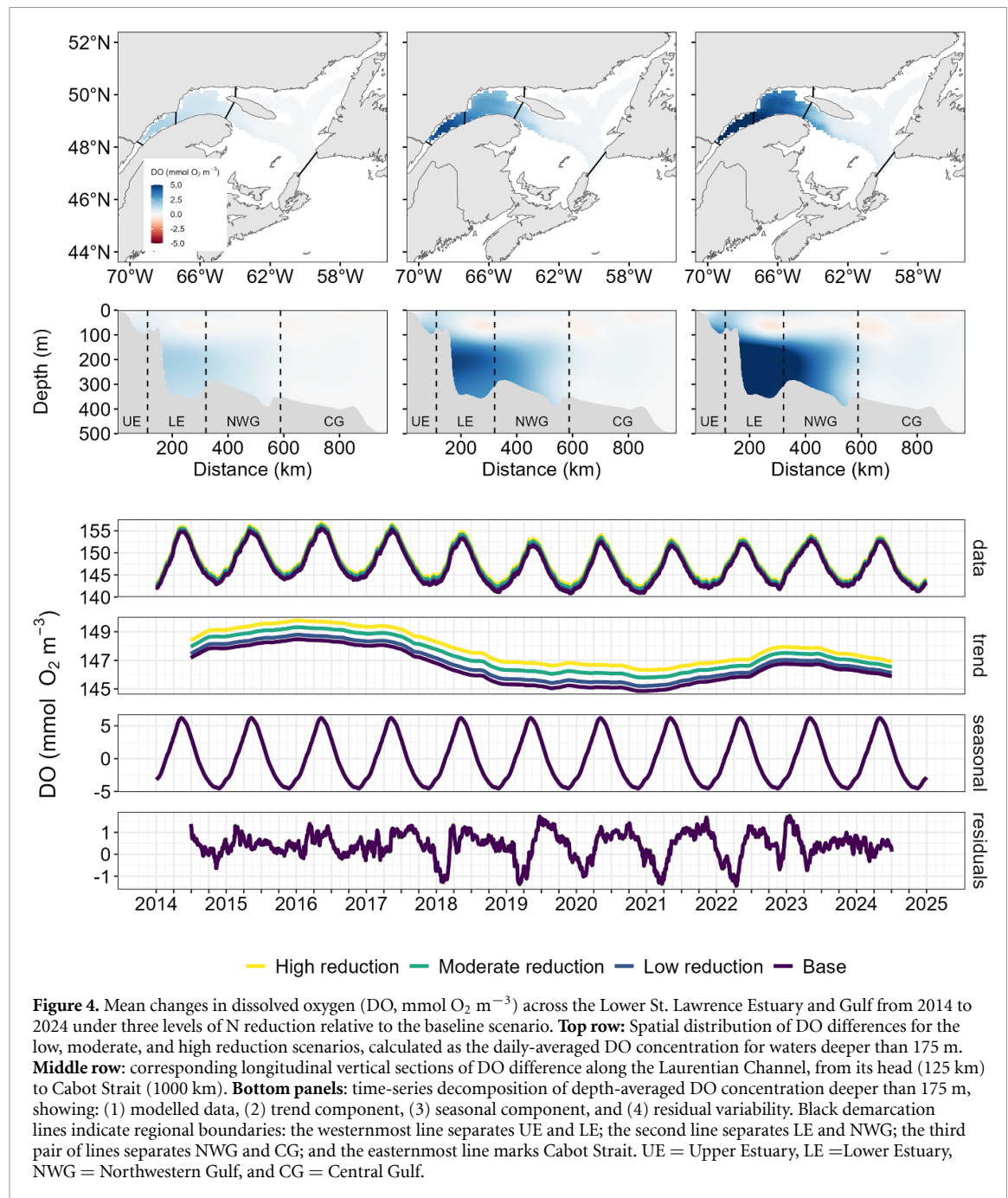
remained consistent across scenarios. Large reductions across all volume indicators occurred during 2022–2024, suggesting a small increase in deep-water ventilation that favoured volume reduction without large concentration changes.

3.2. Indicators of hypoxia

Deep DO improvements occurred mainly in the LSLE and northwestern Gulf (figures 4, 5, S3 and S4). DO showed strong seasonality, varying by

~11 mmol m⁻³ annually, peaking in spring and reaching minima in fall (figure 4). This seasonal amplitude was comparable to the mean DO increase under the high-reduction scenario, whereas inter-annual deep-DO variability was 3-fold smaller (~3.5 mmol m⁻³, figure 4). Across scenarios, DO improvements represented a yield of ~3.6%, calculated using the Redfield ratio (O₂:N = 138:16) and defined as:

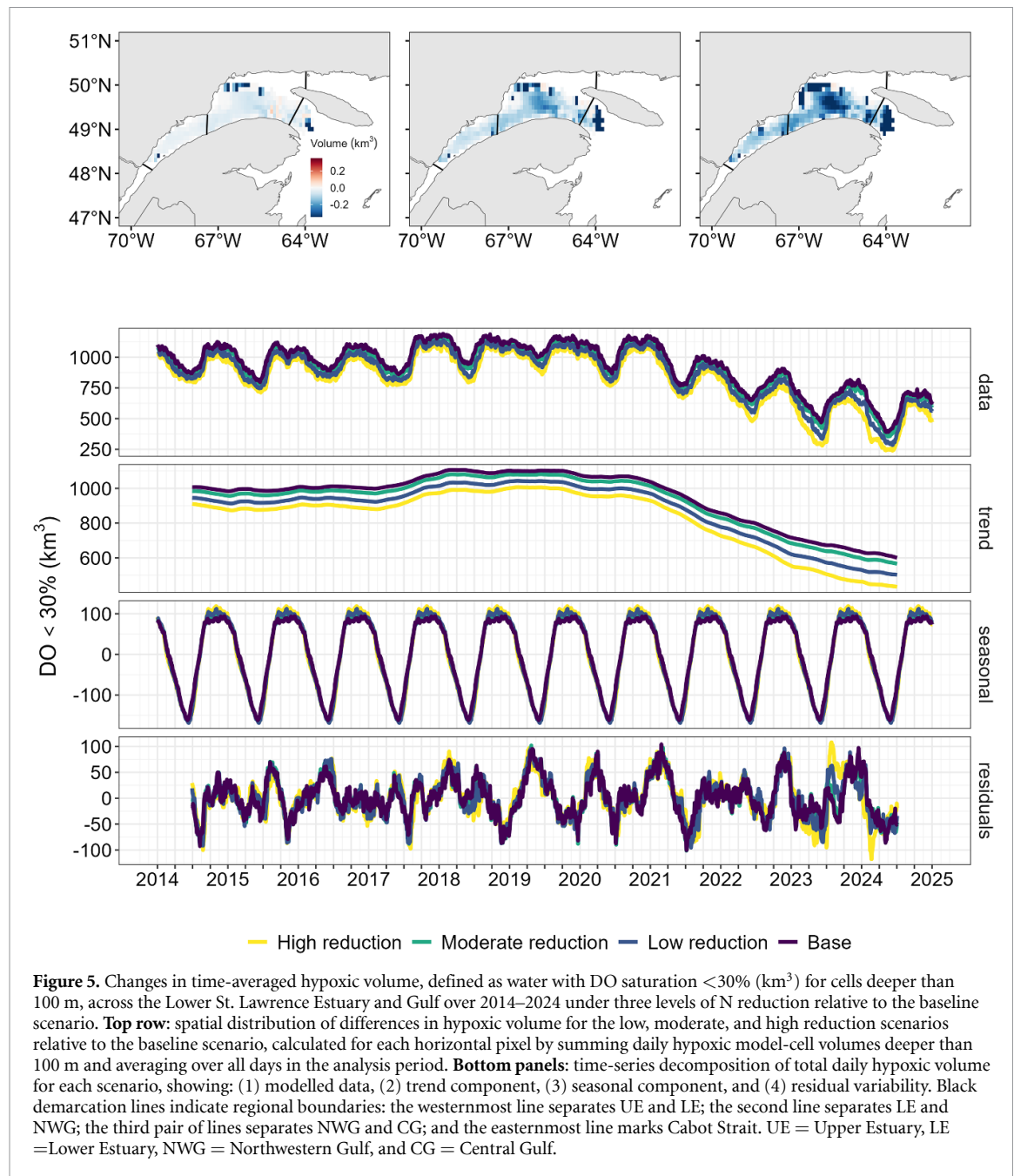
$$\text{Yield}_i (\%) = \frac{\text{Increase in O}_2 \text{ for scenario } i \text{ compared to base scenario}}{\text{O}_2 \text{ equivalent of nitrate decrease for scenario } i} \times 100.$$



This yield represents the efficiency with which reductions in nitrate are translated into improvements in DO, and was comparable to the $\sim 2.2\%$ estimated for Narragansett Bay during 2002–2013 (calculated from figure 3(A) of Codiga *et al* 2022 and figure 6(H) of Wang *et al* 2024) but substantially lower than the $\sim 14.0\%$ estimated for Chesapeake Bay (calculated from figure 6(F) of Kemp *et al* 2009 and figure 6(F) from Lefcheck *et al* 2018).

Hypoxic-water volumes vary annually by $\sim 250 \text{ km}^3$, with smaller volumes following the spring freshet and larger volumes in fall. Oxygenated deep water ($\sim 150 \text{ mmol m}^{-3}$; Jutras *et al* 2023) enters Cabot Strait with inflow strongest from December

to March (Lavoie *et al* 2016). In the model, this seasonal inflow ventilates deep waters, especially the northwestern Gulf. During summer, the model simulates sedimentation of bloom-derived organic matter and enhanced deep respiration (figures 4 and 5). Autumn oxygen minima thus represents the combined effect of organic matter remineralization, the seasonal weakening of deep circulation described by Rousseau *et al* (2025), and poor vertical mixing trapping most hypoxic waters of the LSLE within the Laurentian Channel. Considering only grid cells where the DO threshold was reached, the mean annual (2014–2024) threshold-crossing depth over the Laurentian Channel increased only slightly (max



5 m, $p < 0.001$, table 4). Hence, expansion seems to occur primarily via diffusion toward the wider north-western Gulf.

Our model indicated a nonlinear deoxygenation trend in the EGSL during 2014–2024 (figure 4), consistent with observations since 2015 (Blais et al 2025), but contrasting with the near-linear historical decline of $\sim 1 \text{ mmol m}^{-3} \text{ y}^{-1}$ during 1932–2020 (Gilbert et al 2005, Jutras et al 2023). The baseline scenario showed a mean deep-water DO change of $\sim 2.25 \text{ mmol m}^{-3}$, whereas the high-reduction scenario improved DO 3-fold to $\sim 6.7 \text{ mmol m}^{-3}$ (figure 4). Relative to the observed $\sim 12 \text{ mmol m}^{-3}$ decline at 300 m over the same period (calculated from figure 14 of

Blais et al 2025), this represented a potential alleviation of $\sim 56\%$ of the recent oxygen loss. Previous work attributed most oxygen decline to higher proportions of warm, low-oxygen NACW entering the Channel, with eutrophication contributing a smaller fraction (10%–14%) that increased when warming-driven metabolic acceleration was included (26%–37%) (Jutras et al 2020). If high NACW proportion persists (Jutras et al 2023), future oxygen losses should be driven by warming and microbial metabolism through nutrient loading, supporting the implementation of a comprehensive eutrophication management strategy in the St. Lawrence system.

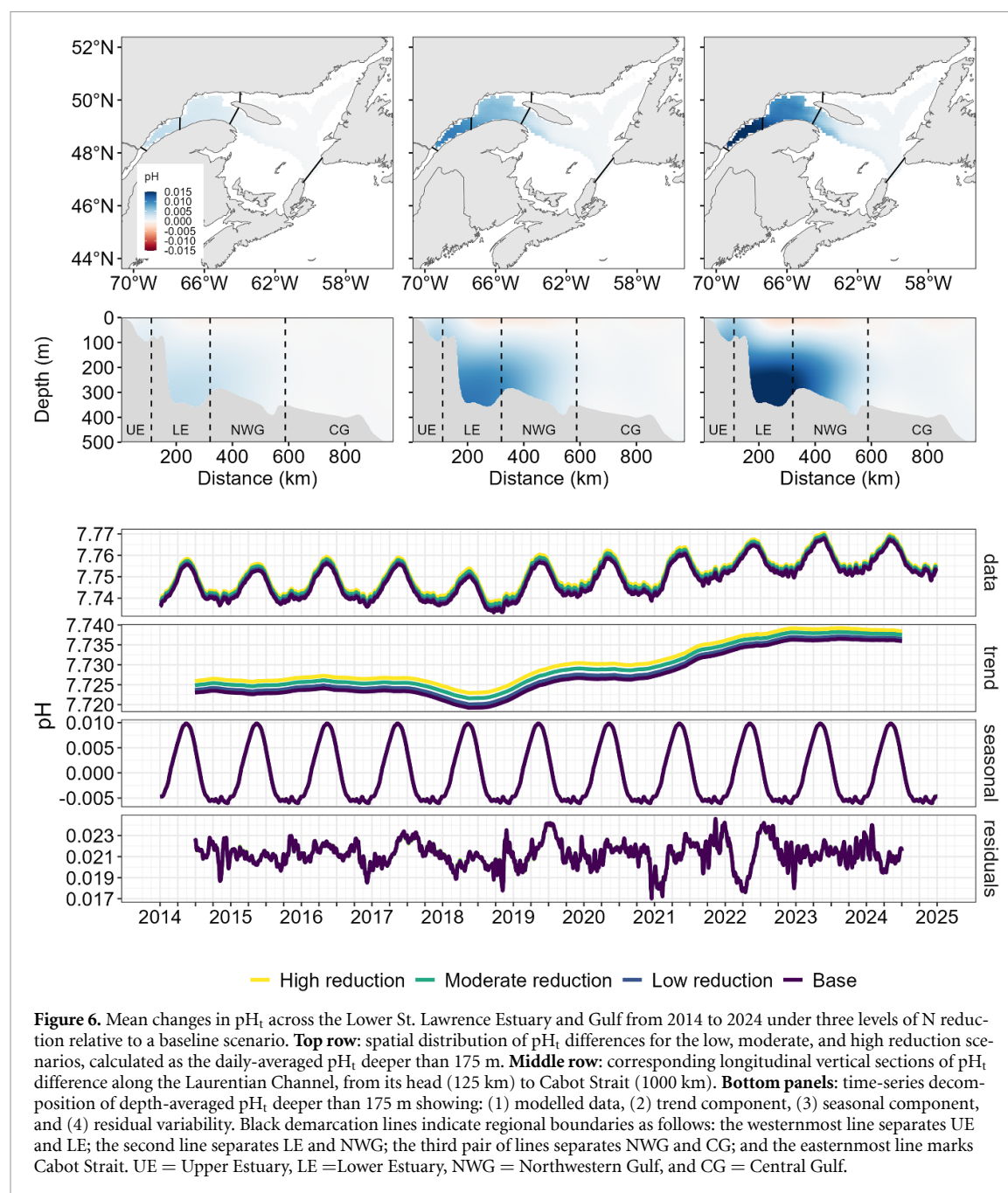


Table 4. Annual means of daily threshold-crossing depth at the centre of the Laurentian Channel for cells where a threshold was reached (m) for hypoxia (30% DO), $pH = 7.6$, and $\Omega_{arag} = 0.6$ under baseline and nitrate-reduction scenarios (2014–2024). Values are reported as mean $\pm$ SD across years.

Scenario	DO saturation depth	pH depth	Ω_{arag} depth
Baseline	214.8 ± 4.0^a	188.2 ± 7.0^a	173.3 ± 5.2^a
Low	216.4 ± 4.1^{ab}	188.7 ± 6.8^a	173.7 ± 5.3^{ab}
Moderate	218.8 ± 3.7^{bc}	188.8 ± 5.8^a	175.4 ± 5.5^{bc}
High	219.9 ± 3.9^c	190.3 ± 6.0^a	176.9 ± 6.5^c

Linear mixed-effect models (scenarios as fixed effect; years as random intercepts, $n = 44$), followed by Holm-adjusted multiple comparisons. Different superscript letters indicate groups that differ significantly at $\alpha = 0.05$.

3.3. Indicators of acidification

Mean deep-water pH_t (figures 6 and S5) and Ω_{arag} (figures 7 and S6) increased progressively across the N-reduction scenarios, mainly in the LSLE and north-western Gulf. Acidified ($\text{pH}_t < 7.65$) and severely corrosive ($\Omega_{\text{arag}} < 0.6$) volumes of water ≥ 100 m fell across scenarios, decreasing acidified and corrosive conditions during the simulation (table 3, figures 8 and S7). As for oxygen, recovery volumes were largest in the northwestern Gulf, where water-mass movement is less constrained by bathymetry (figures 9 and S8). This pattern was supported by no significant scenario differences in mean annual threshold-crossing depth for pH_t (7.6), whereas Ω_{arag} (0.6) showed significant differences, with deeper threshold-crossing depths in the moderate and high scenarios relative to baseline (table 4). The high-reduction scenario produced a modelled pH_t recovery of +0.016, a potential 80% offset compared to the observed ~ 0.02 acidification over the same 11 yr period (calculated from figure 11 of Lizotte *et al* 2026).

The modelled deep-water pH_t improvement under the high-reduction scenario (~ 0.015 relative to baseline) matched both seasonal amplitude and the increase in the pH trend component over 2014–2024 (~ 0.015 , figure 6). Seasonal Ω_{arag} amplitude similarly matched the modelled high-reduction scenario increases (~ 0.015), but interannual variability was larger, increasing by 0.04 for 2018–2024. Low- pH_t water volume fluctuated seasonally by $\sim 400 \text{ km}^3$, with minima after the spring freshet and maxima in fall. This seasonal variability represented $\sim 16\%$ – 18% annual changes across scenarios, exceeding the expected low- pH_t volume associated to a 50% nitrate reduction in the St. Lawrence watershed. Interannual variability in low- pH_t water volume amounted to 400 km^3 , primarily associated with a downward trend from 2018 to 2024. Deep volume with $\Omega_{\text{arag}} < 0.6$ decreased sharply ($\sim 700 \text{ km}^3$) during 2019–2024, with seasonal variation ($\sim 300 \text{ km}^3$) producing a minimum in June and maximum in October (figure 9). Results for Ω_{calc} mirrored Ω_{arag} (figures S9–S12).

The model simulated slight surface pH_t and Ω_{arag} declines in the northwestern Gulf under reduced nitrogen inputs (figures 6 and 7). This was likely caused by lower primary production (table 5), thereby decreasing biological CO_2 uptake and increasing DIC concentrations in surface waters. This response is consistent with other stratified estuaries, where nutrient reductions lower surface pH while improving deep-water carbonate conditions because surface production and deep respiration are weakly coupled (Carstensen and Duarte 2019). Rivers can also deliver more acidified waters than seawater (Borges and Gypens 2010, Carstensen and Duarte 2019) contributing locally to coastal acidification. However, in the LSLE, mixing between the highly buffered marine endmember ($\sim 2100 \mu\text{mol kg}^{-1}$

TA, Gibb *et al* 2023) and moderately alkaline St. Lawrence River water ($\sim 1100 \mu\text{mol kg}^{-1}$; Dinauer and Mucci 2017, 2018) reduces the likelihood of important surface acidification. Comparable complexity in carbonate system responses were reported for Chesapeake Bay, where a 60 yr retrospective simulation (1951–2010) showed spatially heterogeneous pH_t trends dominated by riverine alkalization and ocean acidification, with nutrient reduction playing a minor role (Li *et al* 2025).

3.4. Comparative cases facing dual stressors

Eutrophication-driven deoxygenation and acidification in estuaries and shelves have been widely documented through modelling and observations. In Chesapeake Bay, ground-truthed modelling found that halving nutrient loads could reduce summer acidified water volume ($\text{pH} < 7.5$) by up to 25% through lower water column respiration (Shen *et al* 2019). Observations spanning 1986–2015 reported a $\sim 14\%$ nitrite-nitrate decrease resulting in a slight pH increase (+0.03) in the mid-bay bottom waters (Shen *et al* 2020), exemplifying carbonate chemistry sensitivity to nutrient management in stratified, river-influenced systems. In Narragansett Bay, $\geq 50\%$ nutrient abatement increased DO and pH by reducing microbial respiration, partly offset by warming and greater low-pH freshwater inputs (Wang *et al* 2024). These cases demonstrate that nutrient reductions can reduce dual-stressor effects while highlighting the importance of physical drivers and freshwater signals.

3.5. Driving mechanisms of reverse-eutrophication

The simulated reverse-eutrophication response was driven by reduced organic matter production and export following watershed-scale N-reductions. In the LSLE, mean annual daily primary production in the upper 100 m decreased significantly under all N-reduction scenarios relative to baseline, with a maximum 8% decline under high N-removal scenario (table 5). Reduction in organic matter export to depth was indicated by a small but significant decrease in mean annual daily PON inventory deeper than 175 m across all N-reduction scenarios (table 5). Although small relative to the observed organic matter pool in LSLE deep waters (Lévesque *et al* 2023), the simulated decrease in freshly produced PON was sufficient to decrease remineralization, thus reducing deep-water DIC inventories and apparent oxygen utilization (table 5). Response magnitude and pace are further modulated by deep-water ventilation, circulation, spatiotemporal transport lags, and the timing of socio-economic development and management implementation (Kemp *et al* 2009, Dai *et al* 2023).

Modelled changes produced relatively small, nearly linear responses of eutrophication-driven deoxygenation and acidification to nutrient reductions in annual, ecosystem-wide deep-water metrics.

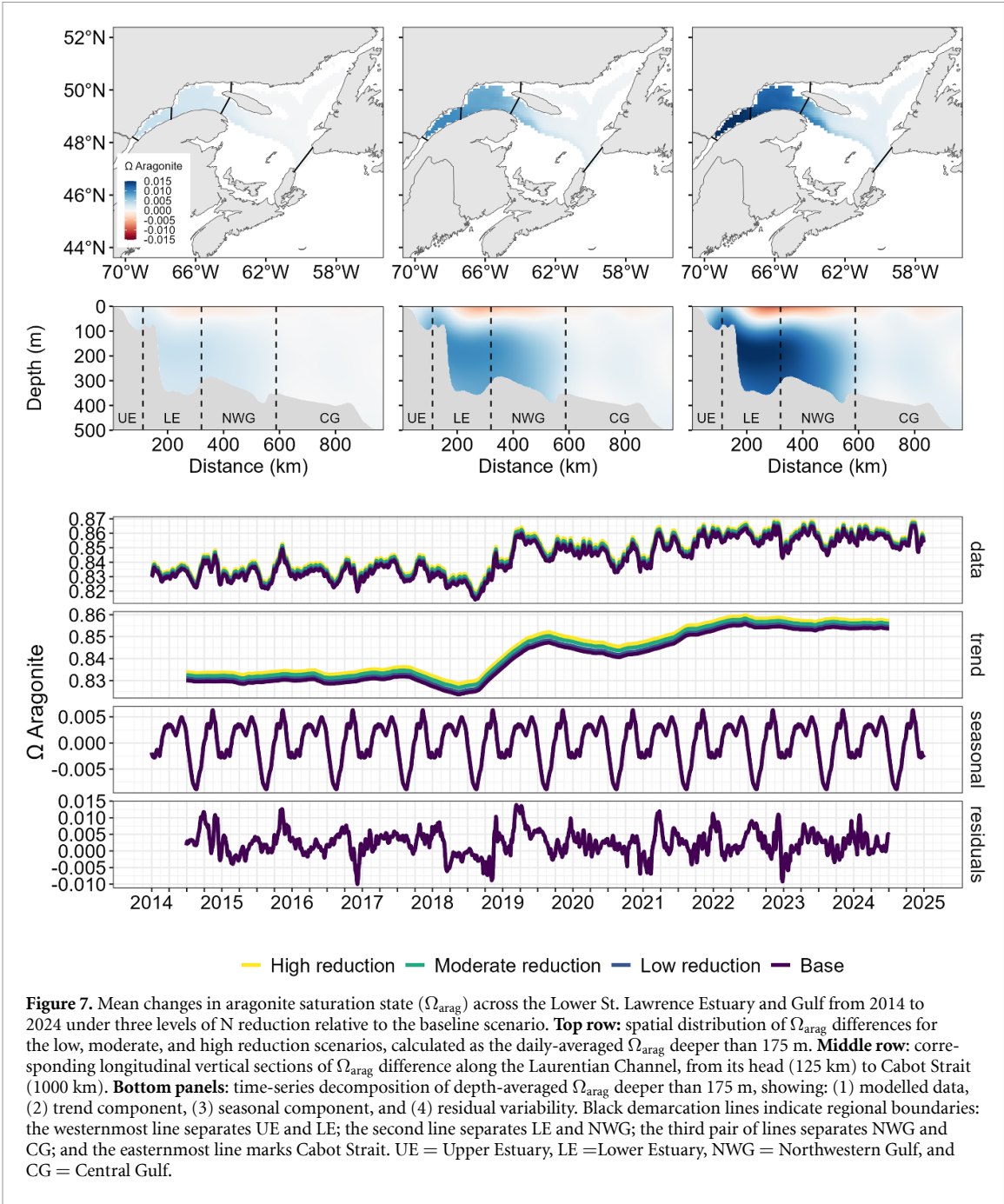
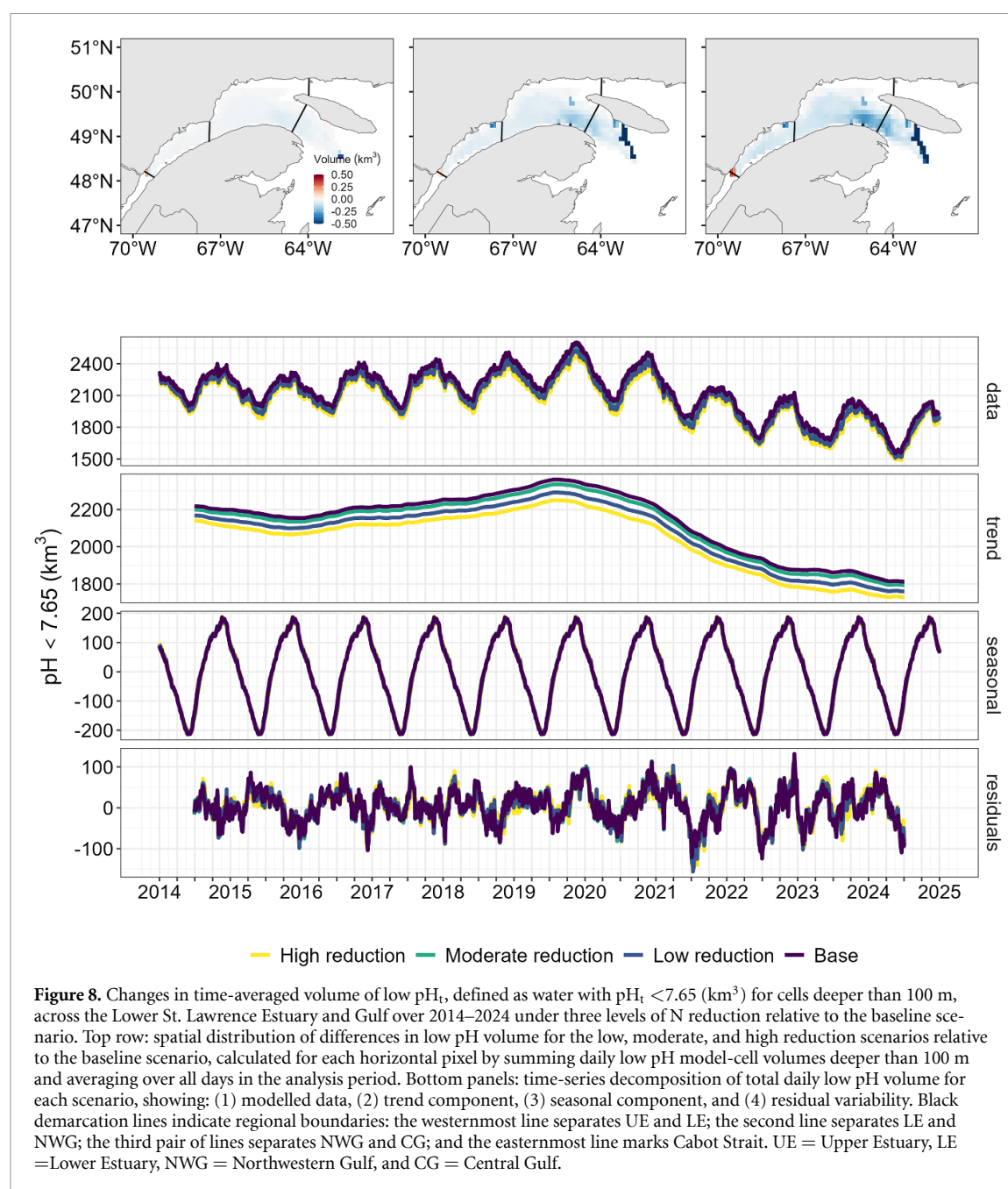


Table 5. Annual means of daily primary production (2014–2024; mean $\pm$ SD) within the upper 100 m of the water column (698.62 km³), and inventories of particulate organic nitrogen (PON), dissolved inorganic carbon (DIC), and apparent oxygen utilization (AOU) in deep waters (≥ 175 m; 407.53 km³) of the Lower Estuary under baseline and nitrate-reduction scenario.

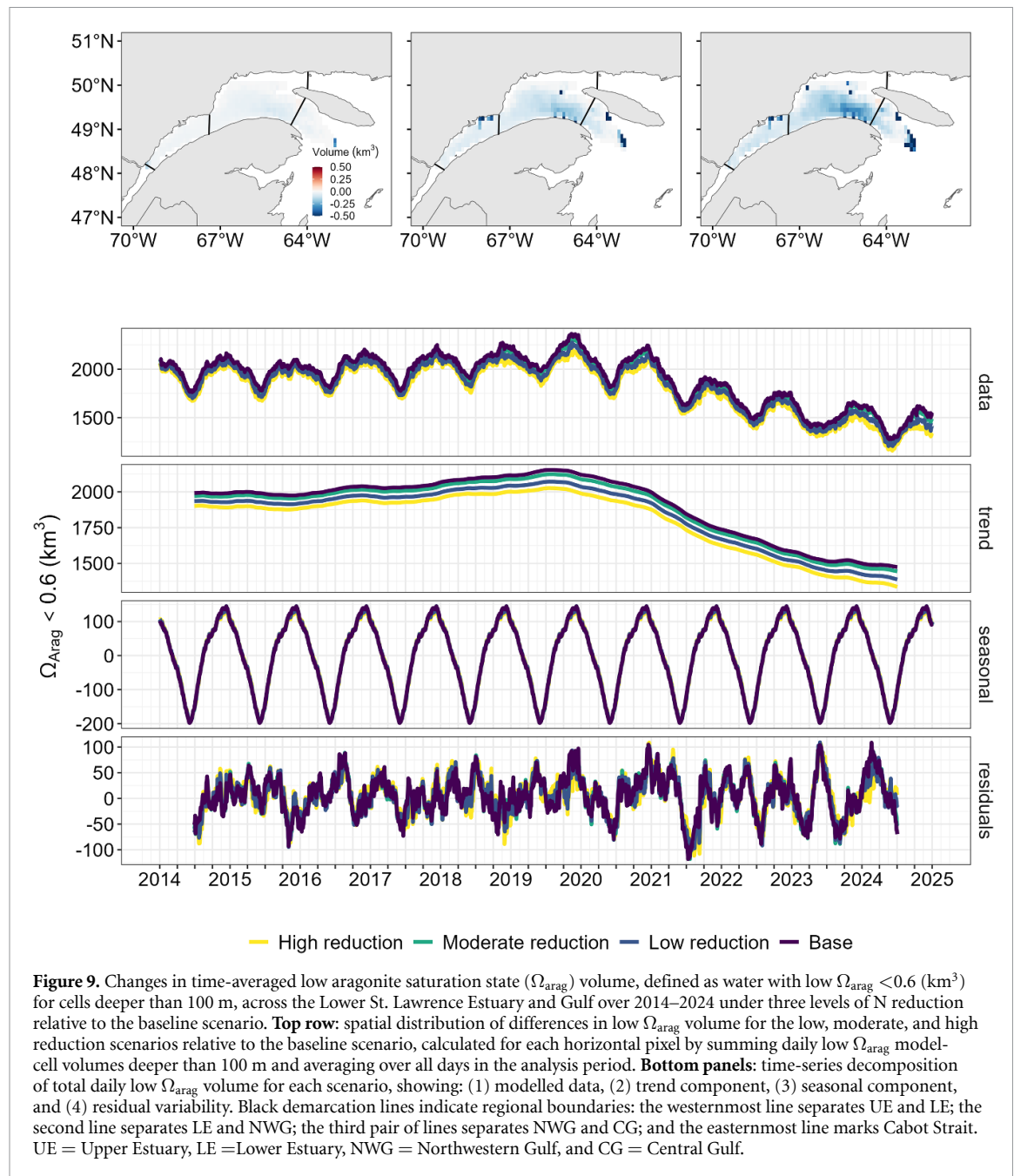
Scenario	Primary production (Gg C d ⁻¹)	PON (Gmol N d ⁻¹)	DIC (Gmol C d ⁻¹)	AOU (Gmol O ₂ d ⁻¹)
Baseline	1540 $\pm$ 134 ^a	0.1060 $\pm$ 0.0031 ^a	939.68 $\pm$ 2.68 ^a	105.0 $\pm$ 2.9 ^a
Low	1511 $\pm$ 127 ^b	0.1057 $\pm$ 0.0031 ^b	939.28 $\pm$ 2.64 ^b	104.4 $\pm$ 2.8 ^b
Moderate	1462 $\pm$ 116 ^c	0.1051 $\pm$ 0.0030 ^c	938.59 $\pm$ 2.57 ^c	103.3 $\pm$ 2.6 ^c
High	1417 $\pm$ 106 ^d	0.1047 $\pm$ 0.0030 ^d	937.96 $\pm$ 2.51 ^d	102.3 $\pm$ 2.5 ^d

AOU is calculated as the difference between the O₂ concentration at saturation and the observed O₂ concentration. Linear mixed-effect models were applied (scenarios as fixed effect; years as random intercepts, $n = 44$), followed by Holm-adjusted multiple comparisons. Different superscript letters indicate groups that differ significantly at $\alpha = 0.05$.



Changes were mainly located in the LSLE and north-western Gulf and strongest during the growing season. This near-linearity likely reflects the moderate perturbation imposed by the N-reduction scenarios in which nitrate loading was the only modified forcing, limiting confounding effects and preserving the overall St. Lawrence biogeochemical regime. Nitrogen reductions may also generate proportional decreases in organic matter supply and subsequent water-column respiration without triggering a strong shift toward another limiting factor or tipping point. However, the near-linear response may reflect model simplifications, such as fixed stoichiometric ratios and constant remineralization and burial

rates, limiting the representation of environmentally responsive biogeochemical processes and nonlinear feedbacks (Andrews *et al* 2017, Fennel *et al* 2022). Furthermore, the large volume of deep waters, their multi-year transit time (Rousseau *et al* 2025), and the modest contribution of sediment legacy effects relative to water-column remineralization (Bourgault *et al* 2012, Alkhatib *et al* 2013) may have further dampened nonlinear or hysteretic responses. Similar quasi-linear responses have occurred in other estuaries (Shen *et al* 2020, Testa *et al* 2022), whereas nonlinearities can emerge under larger loading changes or stronger sediment influence (Kuliński *et al* 2022, Ni and Li 2023).



4. Management implications and conclusions

Reducing St. Lawrence watershed nitrate inputs offers a practical lever to mitigate hypoxia and acidification in the EGSL. While nutrient reduction may not fully counter climate-driven deoxygenation and acidification, our modelling shows it would provide habitat remediation for deep-water taxa in the most impacted region. It is also the only feasible regional control to address these ecological challenges.

Watershed-scale nitrogen management poses major governance and equity challenges in a trans-boundary system spanning eight U.S. states, six Canadian provinces, and numerous Indigenous

territories. The Great Lakes watershed host ~60 million people, largely concentrated in south-western regions except cities such as Montreal, Ottawa, and Québec City (Lamberti *et al* 2023). This geographic and demographic configuration create interregional inequities in environmental problems, benefits, and decision-making power among regions and stakeholders (Fletcher *et al* 2022, Seigerman *et al* 2022). For example, recurrent harmful cyanobacterial blooms in Lake Erie threaten drinking water for ≥11 million people and are managed by P strategies (Schindler *et al* 2016, Watson *et al* 2016). This strategy, rather than a dual-nutrient approach, contributes to EGSL deoxygenation and acidification with cascading ecological and economic impacts

on smaller, more vulnerable populations. Lessons from the Baltic Sea Action Plan highlight effective burden-sharing strategies for nutrient reductions, including sub-basin maximum allowable inputs for nutrients (N and P) and country-level National Input Ceilings (HELCOM 2025). For the St. Lawrence system, a comprehensive basin strategy should integrate (1) wastewater-treatment upgrades with nitrogen removal at major facilities, (2) improved agricultural practices that enhance N-use efficiency, promote recycling, and reduce losses (e.g. precision applications, cover crops, drainage management, riparian buffers) (Malone and Newton 2020, Stokral *et al* 2020), and (3) integrated land-to-sea monitoring under cross-jurisdictional governance (Poikane *et al* 2019). Existing entities and programs should be leveraged, including International Joint Commission, Canada-Québec St. Lawrence Action Plan, First Nations governments, and established monitoring programs such as the Great Lakes Restoration Initiative, Lakewide Action and Management Plans, and Atlantic Zone Monitoring Program.

Our cross-scale results connect watershed management to deep-estuarine habitats, demonstrating how regional N abatement can reshape oxygen and carbonate conditions in deep, stratified coastal ecosystems. Although climate and circulation dominate top-down controls, nutrient reduction remains an actionable and scientifically justified lever. Acting now, guided by models including future climate projections, represents a prudent approach to mitigate current and future severe ecological consequences of deoxygenation and acidification of coastal waters, especially in EGSL.

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Data availability statement

The data cannot be made publicly available upon publication because no suitable repository exists for hosting data in this field of study. The data that support the findings of this study are available upon reasonable request from the authors.

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