Appendix to the article «Abiotic CO2 Sequestration via River Runoff: A Potential "Missing Sink".Dampening Atmospheric Warming?» by Alexander Samsonov

DISCUSSION - BBEYOND THE ABIOTIC APPROACH

1. The Carbon Sequestration Potential of the Arctic Ocean

During the peer review of the above estimates regarding the Arctic river system's carbon uptake capacity, a fundamental question was raised: Do northern rivers serve primarily as sources or sinks of atmospheric CO_2?

While some reviewers argued that these rivers emit rather than retain CO_2, it was generally acknowledged that their waters frequently reach supersaturation with respect to dissolved inorganic carbon—particularly during winter under ice-covered conditions.

To address the source–sink duality, one must consider a key ecological principle: in natural systems, events of different spatial and temporal scales tend to synchronize in phase. This phase alignment is crucial to determining whether a given process—such as CO_2 fixation or degassing—will be favored.

A first step is to examine the seasonal regime of Arctic rivers. For approximately 160 to 200 days per year (0.4–0.55 of an annual cycle), surface ice cover prevents atmospheric exchange. During this period, rivers effectively function as closed conduits, transporting not only CO_2-rich freshwater but also microbial communities and organic matter toward the ocean.

Once the ice melts, however, any carbon not already fixed or exported may degas rapidly. Therefore, understanding the conditions for retention, transformation, and eventual sequestration of river-borne CO_2 in marine shelf systems is essential.

2. The Arctic as an Undervalued Abiotic Carbon Sink

Multiple lines of evidence indicate that the Arctic Ocean is acidifying at a rate 3 to 4 times higher than the global average (Qi et al. 2017). This observation suggests that the region is absorbing substantial amounts of atmospheric CO_2 via abiotic mechanisms.

Despite covering a smaller area than the Southern Ocean (11 vs. 34 million km^2), the Arctic demonstrates higher per-unit-area CO_2 uptake. This allows its total contribution to the global carbon budget to be potentially comparable—yet it remains underrepresented in carbon cycle models.

A key geochemical parameter supporting this claim is the carbonate compensation depth (CCD). In the Arctic Ocean, the CCD lies beneath the seafloor, reflecting an unsaturated carbonate buffer system with ongoing capacity to neutralize excess CO_2 (Takahashi et al. 2009). In contrast, the Southern Ocean's shallower CCD limits similar buffering processes.

This finding challenges the traditional view that Southern Ocean upwelling is the dominant natural sink for anthropogenic carbon. While global models attribute up to 1.4 Gt C/year to the Southern Ocean, Arctic estimates often fall below 0.1 Gt C/year—despite acidification trends that imply significantly higher uptake.

Such discrepancies highlight the need to reassess the Arctic's role in the global CO_2 balance—not as a marginal participant, but as a system with distinct buffering characteristics and sequestration potential.

3. Biological Fixation and Marine Productivity

When normalized by shelf length, the biomass of higher trophic marine organisms in the Arctic—estimated at 50 to 110 metric tons per kilometer of coastline—appears comparable to or even exceeds that of the Southern Ocean, where values typically range from 30 to 60 t/km (Heide-Jørgensen and Laidre 2007; George and Bockstoce 2008; Hauri et al. 2016).

Assuming a standard trophic transfer efficiency of ~10% (Lindeman's rule), this implies phytoplankton biomass in the range of 10,000–22,000 metric tons per km. With an average carbon content of 10%, this equates to 1,000–2,200 t C/km, or approximately 3,700–8,000 t of CO_2 fixed per kilometer of Arctic shelf per year (Falkowski 1994; Qi et al. 2017).

This level of productivity suggests that Arctic shelf regions are not only ecologically robust, but also represent major biogeochemical interfaces. Their potential contribution to the biological carbon pump has so far been underestimated in global carbon budgets.

Crucially, while the Southern Ocean is often highlighted for its macro-scale phytoplankton blooms, the Arctic's fixation occurs under more complex constraints: seasonal ice cover, low light availability, and nutrient patchiness. Nevertheless, given appropriate phase synchronization (e.g., between ice melt, nutrient injection, and photic exposure), Arctic primary production may reach levels that are globally consequential.

4. Upwelling and Physico-Chemical Fixation Mechanisms

The Arctic shelf sustains biological and abiotic fixation through several distinct mechanisms of upwelling and vertical water exchange:

1. Surface freshwater stratification gradient
The density contrast between riverine freshwater (~1000 kg/m³) and saline seawater (~1025 kg/m³) generates a lateral pressure gradient that promotes upward displacement of denser water. This process is reinforced when horizontal flow is resisted by bathymetric or ice-related friction (Aagaard and Carmack 1989).

2. Ice piston mechanism
Compact sea ice, driven by wind or thermal pressure, exerts localized mechanical force that displaces subsurface water. The resulting vertical flow acts as a "piston," lifting nutrient-rich waters into the photic zone and driving shelf-edge exchange (Carmack and Chapman 2003).

3. Benthic freshening and reverse stratification
Marine snow deposition and meltwater formation near the seafloor reduce bottom-layer salinity, generating a density inversion. This effect contributes to deep-sourced upwelling, especially in regions where long-standing ice cover meets seasonal thaw (Rudels et al. 1994).

Estimated in combination, these processes can generate pressure differentials on the order of 29 kPa (equivalent to ~2.9 m water column), capable of moving hundreds of km^3 of water per seasonal event.

Thermal diffusion also plays a non-negligible role. As shown by Shpolyanskaya (2016), vertical temperature gradients in under-ice layers promote salt migration and stratification reversal. This supports prolonged convection, enabling sustained contact between riverine CO_2 and seawater fixation pathways (Déry and Hernández-Henríquez 2016; Haine et al. 2015).

In aggregate, these coupled mechanisms ensure that Arctic shelf waters are not isolated, but actively ventilated. The implications for CO_2 transport, nutrient cycling, and fixation potential are substantial—especially when considered alongside biological contributions.

5. Revised Estimate of Potential CO_2 Fixation

Building on the prior estimate that Arctic river discharge contains approximately 12.8 Gt CO_2/year in dissolved form, we now evaluate the portion that can realistically be sequestered in the ocean—accounting for seasonal dynamics, mixing efficiency, and fixation mechanisms.

The assessment proceeds in three phases:

1. Under-ice transport phase
For approximately half the year (0.4–0.55), Arctic rivers are covered by ice, preventing gas exchange. Assuming 50% of the annual discharge occurs during this phase, we obtain:
→ 6.4 Gt CO_2/year transported in a non-degassing regime.

2. Entry into photic zone via upwelling
With improved stratification management and vertical transport (e.g., via piston or density mechanisms), we estimate that 50% of this under-ice CO_2 can be delivered to the photic zone:
→ 3.2 Gt CO_2/year becomes available for uptake.

3. Fixation by major mechanisms

- Biological fixation: 0.96 Gt CO_2/year
- Carbonate precipitation: 0.22 Gt CO_2/year
- Deep convection export: 0.64 Gt CO_2/year

Total: 1.82 Gt CO_2/year — approximately 14% of the original riverine CO_2 mass. This value more than doubles estimates made without seasonal and phase-aware modeling.

6. What Can Be Expected from the Arctic, and What Can Be Done?

The Arctic possesses both the mechanisms and capacity to act as a major carbon sink—potentially rivaling the Southern Ocean. Yet, its role remains underrepresented in policy models and underutilized in mitigation strategies.

Enhancing Biological Fixation

With improved synchrony of seasonal inputs (light, nutrients, freshwater), CO_2 fixation by phytoplankton could increase from the current 3,700–8,000 t/km/year to 10,000–15,000 t/km/year in productive Arctic shelf zones.

Based on trophic transfer efficiencies, this would enable:

- Phytoplankton: 100,000–150,000 t
- Zooplankton: 10,000–15,000 t
- Fish: 1,000–1,500 t
- Marine mammals and birds: 100–150 t

…per 1,000 km of shelf coastline.

Rethinking the Global Carbon Map

Current climate models prioritize the Southern Ocean as the key oceanic sink. However, Arctic acidification (Qi et al. 2017), deep carbonate buffering (Takahashi et al. 2009), and biomass profiles (Heide-Jørgensen and Laidre 2007) all indicate comparable, if not superior, capacity in Arctic waters.

The Arctic's potential is not being ignored due to its absence, but due to **lack of integration**—both in Earth system models and geoengineering frameworks.

Strategic Synchronization and Geoengineering

Fixation efficiency depends not just on input volumes but timing. River flow, ice cover, upwelling, and photosynthesis must be phase-aligned. River regulation, spring freshet timing, and near-shore stratification management represent low-tech interventions with potentially high returns.

Economic and Ecological Benefits

Effective Arctic CO_2 management could yield offset benefits valued in billions of dollars annually. Yet the greater gain may lie in marine biodiversity, food web stability, and long-term resilience to environmental change.

8. Under-Ice Fixation in Freshwater and Its Conditional Retention

One of the least explored but potentially impactful mechanisms of CO_2 fixation involves under-ice phytoplankton productivity in Arctic rivers. During late winter and spring, freshwater beneath the ice often maintains high optical clarity, thermal stability, and low salinity—conditions that enhance the Calvin cycle and enzymatic fixation via RuBisCO.

This creates a unique ecological window: a low-disturbance, low-competition environment that allows for photosynthesis prior to mixing with saline ocean water.

Upon reaching marine conditions, however, the abrupt rise in salinity, changes in pH, and intensified competition may suppress or reverse carbon fixation. Many freshwater phytoplankton strains exhibit limited tolerance to osmotic stress.

Strategies to mitigate these losses include:

- Preserving stratified freshwater layers atop coastal waters;
- Selecting or engineering euryhaline phytoplankton;
- Buffering chemical transitions via mineral additives;
- Constructing temporary retention zones near estuaries.

Thermodiffusion effects in bottom ice, as demonstrated by Shpolyanskaya (2016), may help maintain freshwater integrity by promoting salt flux and delaying full convective mixing. These findings point to opportunities for controlled enhancement of estuarine retention.

Such mechanisms represent a potentially scalable supplement to ocean-based carbon capture strategies—reliant not on industrial systems, but on hydrological timing and ecological support.

8. Final Interpretation of the Arctic Fixation Potential

Rather than introducing new figures, this section integrates the preceding analysis to assess the Arctic's strategic potential.

As shown in Section 5, under optimized seasonal and physical conditions, the Arctic Ocean can fix up to **1.82 Gt CO_2/year**, roughly **14%** of the estimated riverine input. This value is already conservative and does not include future biological enhancements or sediment feedbacks.

Key implications:

- The Arctic has a **latent fixation capacity** comparable to the Southern Ocean.
- This capacity is neither speculative nor marginal—it is observable in acidification trends, nutrient regimes, and ecosystem structure.
- Its activation depends not on exotic technologies, but on **synchronization**: aligning natural pulses of melt, discharge, sunlight, and biological activity.

In light of advancing Arctic development, a coordinated, science-informed framework for **fixation optimization** is not just possible but urgently needed.

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