A Decline in Marine Biodiversity Caused by Pollution May Be a Primary Driver of Climate Disruption

GOES Foundation multi-vessel image survey of the North Atlantic, 2021–2023

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This revision updates Dryden & Duncan, Int. J. Environ. Clim. Change 12(11):3414–3436 (2022) with the full survey analysis foreshadowed in that paper.

Abstract

Climate policy has treated carbon dioxide as the single lever for climate change. This paper argues that marine biodiversity, and the ocean surface microlayer (SML) it maintains, is an equally decisive control on the climate, and that pollution is degrading both[1,3]. Water vapour is the dominant greenhouse gas (about 70% of all greenhouse-gas forcing), and its atmospheric concentration is governed not only by temperature but by the lipid-and-surfactant SML that phytoplankton produce across 71% of the planet[3,4,7]. That layer concentrates lipophilic ‘forever’ chemicals, adsorbed onto microplastic and black-carbon soot, to levels far above the underlying water, where they are toxic to the plankton that sustain the ecosystem and life support systems for marine life.[6,10,11].

We previously reported a preliminary survey of the equatorial Atlantic[1,25]; here we present its full analysis. An automated image pipeline measured every particle larger than 20 μm in 352 georeferenced surface samples from 8 sailing vessels, classifying and sizing 51,547 particles. Zooplankton were absent from 93.8% of stations; black carbon was present at 89.8%, microplastic particles at 69.9% and microfibres at 22.4%, with phytoplankton at 81.8%. 99.2% of all particles were smaller than 200 μm. These results, reproduced in crew counts and in a separate set of GPS-tagged images, are consistent with a surface ocean stripped of animal plankton and saturated with combustion and plastic residue. We set out the consequences for the SML, water-vapour feedback, cloud formation and ocean acidification, and conclude that eliminating pollution must sit alongside carbon mitigation if climate disruption and ecosystem collapse are to be avoided. A net-tow survey (120 μm mesh) independently confirmed the scarcity of animal plankton — about 0.2 individuals per cubic metre by day and 0.5 by night, both far below productive-ocean values.

Keywords: climate; plankton; marine biodiversity; pollution; black carbon; microplastic; surface microlayer.

Highlights

A citizen-science survey now resolves 51,547 surface particles at 352 georeferenced North Atlantic stations, the full analysis promised in the 2022 paper[1].

Zooplankton were absent from 93.8% of stations; the surface ocean along the trade-wind crossing is effectively devoid of animal plankton larger than 20 μm.

Black carbon (89.8% of stations) and microplastic (69.9%) are near-ubiquitous and dominate a particle field in which 99.2% of objects are below 200 μm[14,15,16,29,30,31].

Pollutant load rises sharply toward South America, consistent with terrestrial and riverine input[17].

The SML regulates water-vapour pressure, cloud formation and precipitation; its loss, driven by plankton decline, points to climate disruption that carbon mitigation alone cannot prevent[3,7,8].

Eliminating black carbon, lipophilic toxic chemicals and plastic is therefore a climate measure, not only a pollution measure[14,24].

1. Introduction

Every ocean is covered by a surface micro-nanolayer (SML) — an operationally distinct skin, between roughly 1nm and 1000 μm thick, of proteins, carbohydrates and lipids produced by marine plankton, together with particulate organic matter, submicron and microplastic, black-carbon soot and chelated metals[2,3,4]. The SML is a living biofilm: bacteria and nanoplankton held in a mucopolysaccharide gel with the lipids and surfactants. It suppresses turbulence and gas exchange, seeds aerosols and clouds, and slows the escape of water molecules from the sea surface[3,8].

Because water vapour is the largest greenhouse gas (70% of al GHG), anything that governs evaporation governs climate. The conventional model treats atmospheric water vapour as a function of temperature alone (the Clausius–Clapeyron relation) and therefore treats carbon dioxide as the only practical lever[7]. We argue that the SML is a second lever, that it is maintained by plankton, and that pollution is degrading it. This paper sets out the survey evidence for plankton loss and pollutant accumulation, then traces the consequences through the SML to water vapour, clouds, ocean pH and biodiversity.

2. The GOES North Atlantic survey: expanded image analysis

Surface water is the layer that holds most particles and toxic chemicals, yet conventional oceanography samples mainly from 5–200 m and rarely resolves the 20 μm fraction in mid-ocean. The GOES citizen-science project was designed to fill that gap. Crews on ocean-going yachts drew surface samples on a fixed schedule (12;00 hrs and 24;00 hrs), filtered them to ~20 μm, and photographed the filter under microscope whose maximum magnification places a single 5 mm aperture (5000 μm) across the field of view, giving an imaging resolution of about 20 μm.

The 2022 paper reported a preliminary summary of the first crossing (about 500 samples, 2500 images) and noted that a fuller analysis would follow[1,25]. This is that analysis, and it is both larger and quantitative. We assembled the recoverable photographic archive from 8 vessels sampling between 2021 and 2023 along the trade-wind route from the Canary Islands and Cape Verde to the Caribbean and Suriname, with higher-latitude return legs. An automated pipeline (OpenCV) locates the filter aperture, detects every particle larger than 20 μm, measures it against the known 5 mm field width, and classifies it as zooplankton, phytoplankton, plastic particle, plastic fibre or black (combustion) carbon. Each image was tied to a position from its GPS tag or its field-log row. In total the pipeline sized and classified 51,547 particles at 352 georeferenced stations.

2.1 Near-absence of zooplankton

The dominant result is an absence. Zooplankton were not detected at 93.8% of stations, and the entire archive yielded only 44 animal-class objects — the largest things measured (median 328 μm). The absence was not confined to any vessel or region (Fig. 1), and an independent set of 110 GPS-tagged images from a single crossing returned no zooplankton at any point on the track (Fig. 2). Microplastic ingestion and pollutant toxicity are known to suppress copepods and other grazing zooplankton[12,13,16], and a long-term global decline in phytoplankton has also been reported[19,26,27,28]. An independent net-tow survey, by day and by night, confirmed this scarcity directly (§2.6).

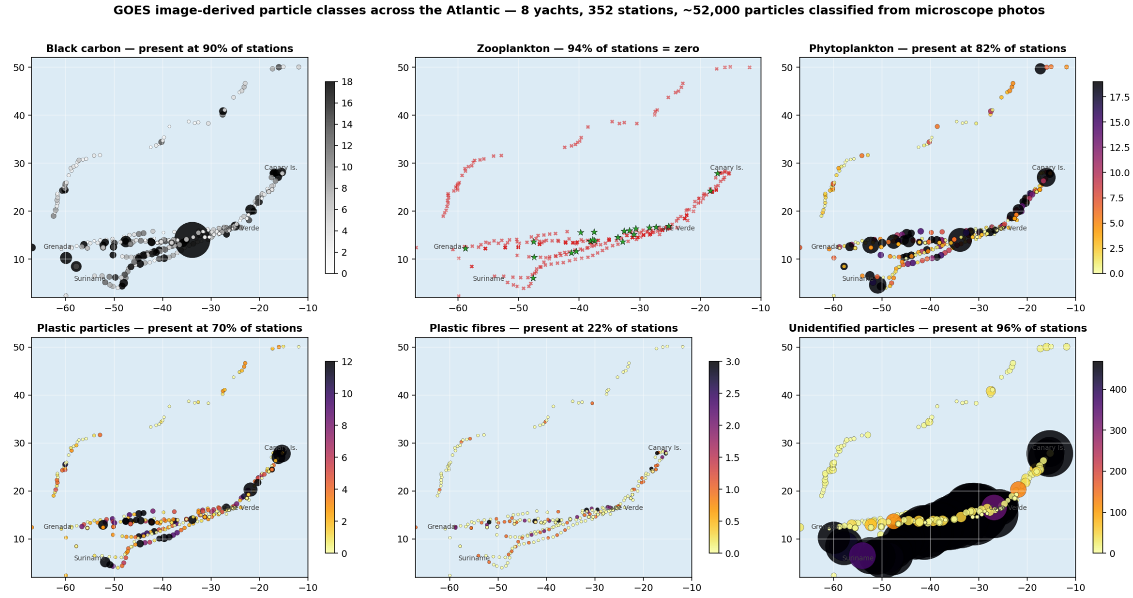

Fig. 1. Image-derived particle classes across the North Atlantic (8 vessels, 352 stations). Zooplankton (top-left) are absent at most stations; black carbon, phytoplankton and plastic recur throughout.

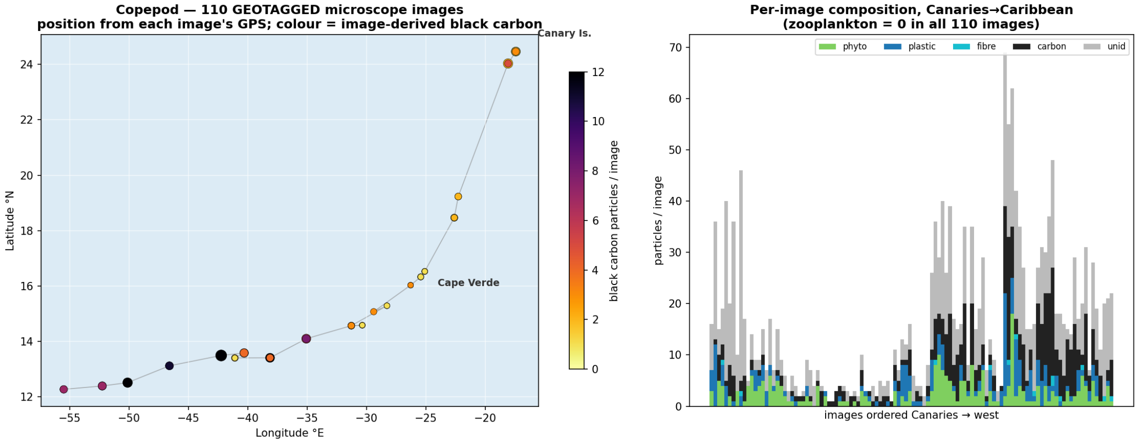

Fig. 2. Geotagged single-vessel sub-survey (110 images, GPS per image). Left: track coloured by image-derived black carbon. Right: per-image composition; zooplankton absent from all 110 images.

2.2 Ubiquitous black carbon and microplastic

Against that empty animal background, anthropogenic particles were near-universal. Black carbon was present at 89.8% of stations (3,559 particles; median 31 µm), microplastic particles at 69.9% and microfibres at 22.4% (median fibre length 204 µm). Phytoplankton-class objects were present at 81.8% of stations. Plastic and black carbon are now documented throughout the open ocean, including the Atlantic water column, the remote marine atmosphere and polar snow[14,15,16,18,29,30,31], so the pervasiveness seen here is expected. Expressed as concentrations (Table 1; each 5 mm field passes ~100 mL, so per-litre = particles per field × 10), black carbon spanned about 0–52 /L (median 12, maximum ~1,304), phytoplankton 0–50 /L and microplastic particles 0–40 /L, while zooplankton stayed at or near zero (0–22 /L). Load increased markedly toward the western basin and the South American shelf, the direction of greatest river and terrestrial input[17] (Fig. 3).

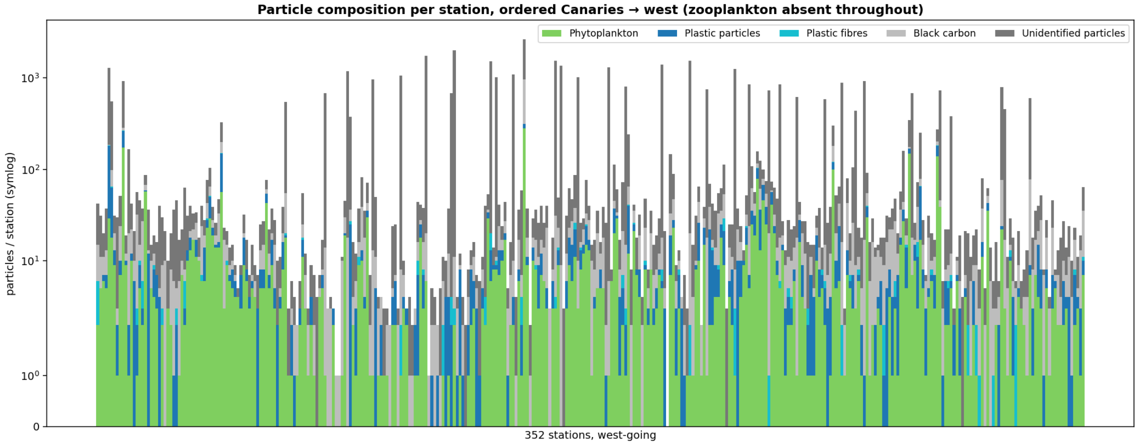

Fig. 3. Per-station particle composition ordered west from the Canary Islands. Zooplankton are flat at zero; carbon, plastic and unidentified material dominate and rise toward South America.

2.3 The surface field is overwhelmingly sub-200 µm

The particle field was very small: 99.2% of all classified particles measured below 200 µm, bunched against the 20 µm filtration and imaging limit (Fig. 4). Plastic fibres formed a distinct larger mode (median 204 µm) and the rare zooplankton occupied the >200 µm range. Because abundance is concentrated at the smallest resolvable size, the true particle burden — including the submicron fraction that the SML preferentially binds — is certainly higher than these counts, which should be read as a floor.

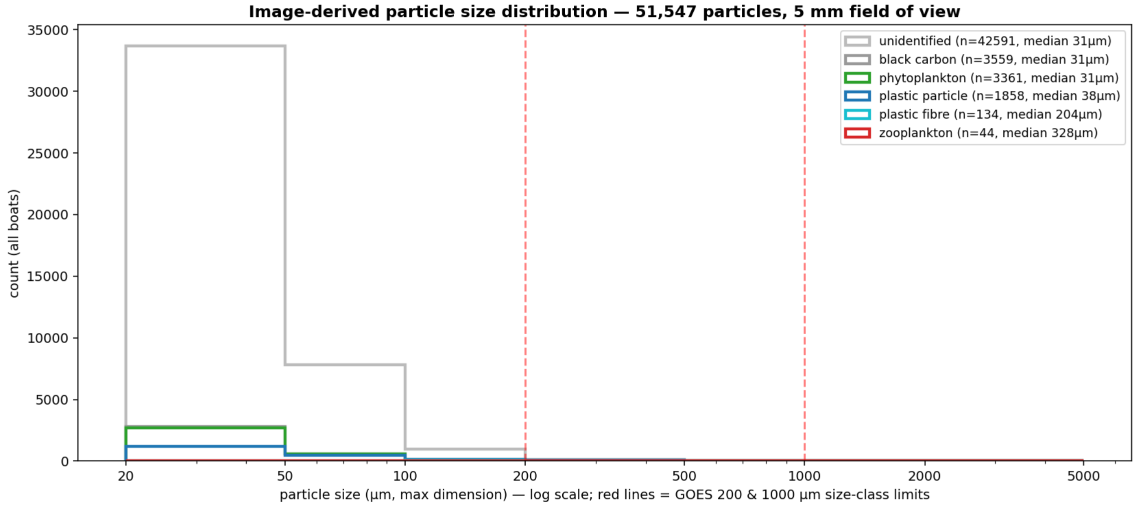

Fig. 4. Image-derived particle size distribution by class (log axis; dashed lines mark the 200 and 1000 µm boundaries).

2.4 Validation and limitations of the classification

We validated the pipeline against one vessel leg counted by hand. The two agreed on the points that carry this paper: zero zooplankton at every station, and a load dominated by carbon and fine unresolved material (Fig. 5). They diverged on the split between plastic and phytoplankton, where the algorithm leaned toward plastic and the human toward phytoplankton. We therefore treat the zooplankton-absence and total-load signals as firm and the plastic-versus-algae partition as provisional. ‘Black carbon’ here is an optical description — dark, colourless particles — and could include sediment, shadow or dark plastic; confirming its composition requires spectroscopy. These are microscope images from an opportunistic citizen-science programme without blank controls or standardised optics, so fibre counts in particular may include airborne contamination, and only the 20 µm–5 mm window was imaged. The filter tube was covered by a cap; only when the filter paper was removed from the assembly would there be a risk of contamination. It is, therefore, considered to be minor.

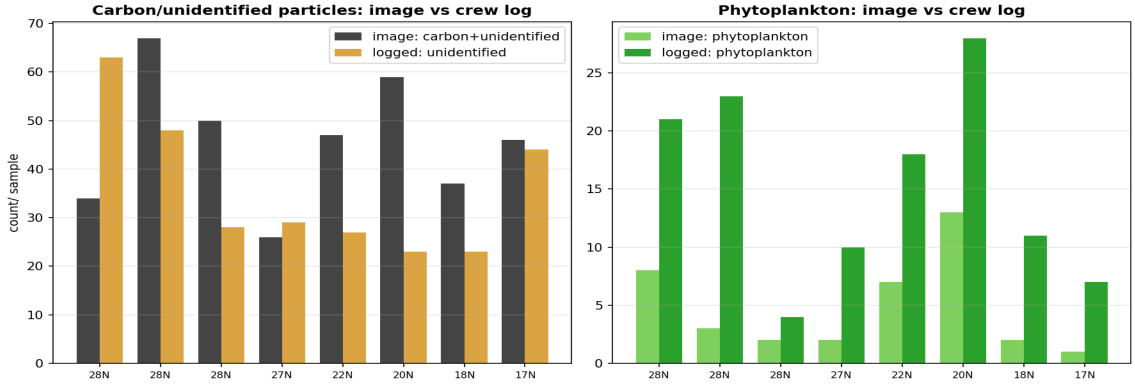

Fig. 5. Automated versus hand counts for one leg. Carbon and total load track the human counter closely; the plastic-versus-phytoplankton split is the main disagreement.

2.5 Survey at a glance

Metric / class	This revision — stations	This revision — particles per litre
Vessels	8 (2021–2023)	—
Images / particles	51,547 classified	—
Georeferenced stations	352	—
Zooplankton (>20 µm)	absent at 93.8%	≈0 /L typical (max 22)
Zooplankton (net tow, day)	present in all 10 tows	≈0.22 /m³ ≈ 1 per 4,500 L
Zooplankton (net tow, night)	present in all 4 tows	≈0.46 /m³ ≈ 1 per 2,180 L
Phytoplankton (>20 µm)	present at 81.8%	0–50 /L (median 10, max 562)
Black carbon	present at 89.8%	0–52 /L (median 12, max 1304)
Plastic particles	present at 69.9%	0–40 /L (median 5, max 378)
Plastic fibres	present at 22.4%	0–2 /L (median 0, max 20)
All particles	—	0–130 /L (median 35)
Size structure	99.2% of particles < 200 µm	—

Table 1. Survey at a glance. Per-litre concentrations are derived from the image counts on the basis that each 5 mm filter field passes ~100 mL of seawater (per-litre = particles per field × 10); ranges span the 10th–90th percentile across stations, with median and maximum in parentheses. These counts include only particles ≥20 µm resolved in the imaged field and are therefore conservative; the lower black-carbon figures relative to the 2022 estimate (100–1000 /L) reflect this resolution limit and the exclusion of the sub-20 µm fraction the SML preferentially binds.

2.6 Independent confirmation by net tow, day and night

To test whether the near-absence of zooplankton in the surface grab samples was an artefact of the small sampled volume, a concentrating plankton net was towed in the mid-Atlantic. A 120 µm mesh net of 0.30 m mouth diameter was towed at about 2 knots for 10 minutes per haul; each haul therefore strained roughly 43,600 litres (mouth area 0.071 m² × ~617 m towed). Because many zooplankton migrate downward by day and rise toward the surface at night, the net was towed in two sets: ten hauls in daylight (12:00–15:00) and four after dark.

Zooplankton were recovered in every haul. The ten daytime hauls returned 5, 10, 2, 13, 4, 7, 27, 6, 9 and 14 individuals (97 in ~436,000 litres), a concentration of about 0.22 per cubic metre, or one animal per 4,500 litres. The four night hauls returned 25, 15, 32 and 8 (80 in ~175,000 litres), about 0.46 per cubic metre, or one per 2,180 litres (Table 2). The night surface density is roughly twice the daytime value, exactly the pattern expected from diel vertical migration — but the decisive point is that even at night, when surface-living and migrating zooplankton are both present, the standing stock is only about half an individual per cubic metre.

This removes the main alternative explanation for the image survey: the surface scarcity is not simply an effect of small sample volume or daytime timing. Two methodological caveats remain — the 120 µm mesh retains larger taxa while passing the smallest copepods and nauplii, and filtered volume is computed from tow geometry rather than a flow-meter — so the standardised, replicated net sampling recommended below would refine the absolute figures. A surface zooplankton stock of 0.2–0.5 per cubic metre, day and night, nonetheless sits far below densities typical of productive open ocean.

Net tow (120 µm, 0.30 m, ~2 kn × 10 min)	Daytime (12:00–15:00)	Night
Number of hauls	10	4
Zooplankton per haul	5, 10, 2, 13, 4, 7, 27, 6, 9, 14	25, 15, 32, 8
Mean per haul	9.7	20.0
Total caught / volume filtered	97 in ≈436,000 L	80 in ≈175,000 L
Concentration	≈0.22 m^{-3}	≈0.46 m^{-3}
Equivalent	≈1 per 4,500 L	≈1 per 2,180 L

Table 2. Net-tow confirmation of zooplankton scarcity by day and night (mid-Atlantic). Filtered volume is the swept volume of the net mouth (area × tow distance); concentrations assume complete filtration and are therefore upper-bound counts per unit volume. Night density is ~2× daytime, consistent with diel vertical migration, yet remains below 0.5 m^{-3}.

3. Sources of marine pollution and their implications

The SML attracts lipophilic ‘forever’ chemicals, microplastics and hydrophobic black-carbon soot from incomplete combustion of fossil fuels and trees. Measured concentrations of toxic chemicals in the SML can be hundreds of times higher than in the water below[6], so the layer acts as an accumulator at the precise interface where plankton live. Hydrophobic black carbon and plastic particles preferential adsorb these lipophillic chemicals and carry them into the base of the food web[11,14]; partially combusted carbon behaves much like plastic in this respect, a point that has been largely overlooked. The survey shows both classes are present across the open Atlantic far from land[15,16], so this is an open-ocean phenomenon, not a coastal one.

4. The surface microlayer, aerosols, clouds and evaporation

Phytoplankton lipids and surfactants build the SML[4,9], which seeds the marine aerosols around which water vapour nucleates[8] and clouds form, and which simultaneously slows evaporation and the transfer of heat to the atmosphere[7]. A healthy SML therefore cools the surface, promotes cloud formation and precipitation, and moderates humidity. Degrade it and evaporation rises, atmospheric water vapour increases, and cloud formation shifts toward fewer but more violent downpours. Because the increase in atmospheric water vapour is sourced almost entirely from the ocean, the state of the SML is a first-order climate variable that is absent from conventional carbon-only models. The primary mechanism controlling the climate may have been neglected

5. Ecosystem regime shift and ocean acidification

Toxic loading kills the grazing zooplankton first[12,13]; the survey’s near-total absence of animals is consistent with that. Ungrazed phytoplankton bloom, exhaust nutrients and sink, leaving high-nutrient low-chlorophyll (HNLC) water that is spreading in the open ocean; roughly 30% of the world’s oceans and 80% of the Southern Ocean are now categorised as

HNLC zones[20] and they are expanding at a rate of 1-2% year on year. As primary production falls[19], less carbon is fixed at the surface and dissolved CO2 rises;

Synthetic Aperture Radar (SAR)—satellite surveys should be expanded to look at ocean surface ripples. The data can be used to map the SML, microplastic and partially combusted carbon pollution. It is an indirect method of measuring redox potential, zeta potential, surface tension and even oxygen concentration. It's a measure of marine productivity and concentration of diatoms and coccolitophores.

The carbonate-forming coccolithophores and the diatoms that build the SML are among the first casualties of falling pH[21,22]; their loss thins the SML further, closing a feedback between acidification, plankton loss and evaporation. On the trajectory described in the original paper, a regime shift past pH ~7.95 revised to 2035 would collapse the SML and the carbonate base of the food web together[1,21]. Ocean acidification is considered the evil twin of climate change, evil because the consequences will be far more serious. A total regime shift in the world’s oceans, which could potential happen over the next 10 years, is an existential threat to the survival of humanity.

6. Carbon dioxide and marine biodiversity

Carbon dioxide still matters: even at net zero, atmospheric CO2 would remain high enough to keep acidifying the ocean, and acidification is driven by chemistry the survey cannot reverse[21,23]. The argument here is additive, not dismissive — carbon mitigation is necessary but not sufficient. Without also removing the pollution that is killing surface plankton, the SML will continue to degrade, and the climate and biodiversity consequences will follow regardless of the carbon trajectory. A potential remediation strategy includes the dispersal of 10 billion tonnes of 100-micron olivine mineral throughout the world's agricultural land. The mineral would remove most of the anthropogenic carbon dioxide and help buffer the world's oceans against declining pH. The iron component in olivine would help with the photo-oxidation of toxic organic chemicals and help promote the growth of phytoplankton. The silica component would preferentially support the growth of diatoms that sustain the SML.

7. Conclusion

The expanded survey strengthens the central observation of the 2022 paper and puts numbers behind it: across 352 stations and 51,547 particles, the trade-wind Atlantic carries almost no animal plankton larger than 20 μm and a great deal of combustion and plastic residue, with the smallest size classes dominant. Whether or not every mechanism in the SML hypothesis is settled, a surface ocean this depleted of plankton and this saturated with anthropogenic particles is a system under severe stress, of the kind that precedes abrupt ocean ecosystem shifts[34,35].

Carbon dioxide emissions must fall as a matter of urgency. But carbon mitigation alone will not stop ocean acidification or the loss of the SML. We must also eliminate the discharge of black carbon, lipophilic ‘forever’ chemicals and plastic, and aim for a toxic-free world. Pollution is now estimated to be the largest environmental cause of premature human death, and ocean pollution is a direct threat to human health[24,32], and the same discharges burden the ocean surface. Marine plankton are the planet's life-support system and can rebuild quickly once the toxic pressure is removed; regenerating marine life is, on this evidence, a climate strategy in its own right, and potential a critical requirement for the survival of humanity.

8. Recommendations

Continue and accelerate carbon mitigation, but treat pollution elimination as a parallel climate measure of equal urgency.

Eliminate discharge of lipophilic 'forever' chemicals, plastic and black-carbon soot; treat all wastewater; adopt a 'do no harm' standard for land and ocean.

Transition from destructive farming and unsustainable fishing toward rewilding and ecosystem regeneration on land and at sea.

Evaluate raising seawater calcium and alkalinity using lime stone and olivine minerals as a low-risk means of buffering surface pH.

Establish standardised, calibrated surface-microlayer monitoring — building on the citizen-science method here but adding laboratory particle confirmation (FTIR/Raman), blanks and replication — to convert these observations into quantitative time series.

Methods (survey analysis)

Surface samples were collected by participating crews at ~12-hour intervals, filtered to ~20 µm, and photographed on digital microscopes at a 5 mm field of view, with position, date and time logged. Positions were taken from image GPS (read from the HoudahGeo database for the geotagged subset) or from the field spreadsheet via the workbook image anchors; mixed degree/decimal-minute coordinates were converted to decimal degrees, with unmarked longitudes assigned West for the survey region. Images were analysed in OpenCV: Hough-circle aperture detection, then segmentation by combined background-subtraction and saturation thresholds; connected components ≥20 µm (max dimension, scaled by 5 mm / image width) were classified by elongation, saturation, hue and darkness, with unresolved objects left unidentified, and every particle sized. The pipeline was validated against one hand-counted leg. Per-station counts, all particle sizes and the crew logs accompany this revision as a supplementary workbook (GOES_ALL_DATA.xlsx).

Net-tow validation: a 120 µm plankton net (0.30 m mouth) was towed at ~2 knots for 10 min per haul — ten daytime hauls (12:00–15:00) and four night hauls, mid-Atlantic; filtered volume was computed as net mouth area × tow distance and zooplankton in each haul counted and expressed per unit volume.

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