

Closing the Spatial-Scale Gap in Marine Plastic Debris Monitoring: An Analytical Case for Autonomous Surface Vehicles in the Pre-Fragmentation Window

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Abstract. The problem of marine plastic pollution is an enduring challenge that poses significant risks to water quality, ecological processes, and public health. When large pieces of debris break down into smaller plastics due to photo-degradation by ultraviolet radiation and abrasion, retrieval becomes impractical, leaving prevention by intercepting debris before it fragments as the sole available solution. In this paper, we develop a qualitative analytical synthesis of the debris-to-microplastic contamination process and highlight the missing link in the intervention measures currently being used. Using polymer-specific photo-degradation kinetics and gyre transport behaviour, we show that effective intervention requires monitoring at an intermediate spatial scale that is not covered by existing methods. We introduce autonomous surface vehicles as a complementary intervention technology, describe a prototype implementation, and develop a multi-vehicle strategy based on oceanographic accumulation analysis. The contribution is conceptual rather than empirical: the prototype has not yet been field-deployed and the multi-vehicle architecture has not been simulated, leaving field testing as the next step.

Keywords: marine plastic pollution · microplastic prevention · pre-fragmentation window · autonomous surface monitoring · ocean gyre dynamics · spatial-scale gap · multi-vehicle deployment.

1 Introduction

1.1 The pre-fragmentation imperative

The contamination of water bodies by plastic wastes has become one of the most significant water-quality problems in the twenty-first century. The quantity of plastic waste discharged into the ocean from land sources in 2010 ranged from 4.8 to 12.7 million metric tonnes (Mt) annually [1]. In updated figures, the amount of plastic released into aquatic ecosystems in 2016 has been placed between 19 and 23 Mt, and the projected value in 2030 is expected to rise to 53 Mt if business-as-usual continues [2]. Standing stock estimates for floating plastics increased from 5.25 trillion pieces in 2014 [3] to between 82 and 358 trillion pieces by 2019 [4].

It is important to emphasize that the significance of this pollution does not lie in its quantity but rather in its trajectory through the scale of sizes. After entering the aquatic environment, plastic pollution is further broken down by means of ultraviolet radiation, mechanical abrasion, and temperature changes from macroplastic (>25 mm) into mesoplastic (5–25 mm), followed by microplastic (<5 mm) and finally nanoplastic particles. The breakdown process is essentially irreversible on a global ocean scale because, while large debris can still be collected mechanically, microplastics spread over thousands of cubic kilometres of seawater cannot be feasibly extracted [5,6]. After formation, microplastics enter the marine food web and raise human-exposure concerns [7,8].

Irreversibility forms the foundation for the pre-fragmentation window—the time period from when debris enters the marine ecosystem up to the point where degradation to microplastic scale makes recovery infeasible. The span of this window depends on the polymer, varying from a few years for thin polyolefin films to several centuries for rigid polyethylene products [9], but its existence is what frames the intervention problem.

1.2 Contribution and structure

Our paper makes an analytical argument for autonomous surface monitoring as a missing element of the marine debris intervention ecosystem. Our contribution lies in the environmental analysis itself rather than in any specific engineering implementation. We will (i) characterize the contamination process from a polymer-specific perspective, (ii) derive monitoring requirements from oceanographic accumulation dynamics, (iii) identify a particular spatial-scale gap that current monitoring approaches do not occupy, and (iv) propose autonomous surface monitoring as a complement, not substitute, to current solutions. We use a prototype system named Ocean Voyager to illustrate our concept, but the system is the response to the analysis, not its subject.

We emphasize at the outset that this paper is conceptual. The analytical framework it develops is qualitative: it synthesizes published degradation kinetics and oceanographic transport dynamics to localize a coverage gap on a resolution-versus-coverage plane, rather than proposing equations, a numerical scoring scheme, or a quantitative selection workflow. No new field measurements or simulations are reported, and neither the prototype nor the multi-vehicle architecture has been field-tested; the value of the paper lies in the synthesis and the gap it identifies.

The paper proceeds from the contamination pathway (Section 2) and ocean-dynamic accumulation processes (Section 3) to a review of existing methods and the spatial-scale gap they leave open (Section 4), then derives system requirements, introduces the prototype, and outlines the deployment concept (Section 5), before discussing limitations and conclusions (Sections 6 and 7).

2 The Debris-to-Microplastic Contamination Pathway

2.1 Polymer-specific degradation kinetics

Degradation of plastic materials within marine ecosystems takes place mainly through photo-oxidation caused by UV-B light and abrasion due to waves, followed by thermal changes and partial hydrolysis. This process starts with free-radical chain reactions, producing carbonyl groups, polymer chain scission, embrittlement, and ultimately fragmentation [10,11].

Sensitivity to this mechanism differs considerably among polymer types. Polyolefins—polyethylene (PE) and polypropylene (PP)—accounting for about 50% of total worldwide plastic output, are especially vulnerable. The chemical industry employs nearly 70% of worldwide UV stabilizers to safeguard these polymers [12]. Polyethylene terephthalate (PET) absorbs near-UV light better than polyolefins but possesses a smaller photo-degradation quantum yield, rendering it more resistant in practice. Polystyrene is extremely sensitive to UV exposure, whereas polyvinyl chloride degrades through a separate dechlorination pathway.

Degradation rates have been harmonized using the specific surface degradation rate (SSDR) framework [9]. In the case of HDPE in marine settings, SSDR ranges between roughly 0 to 11 μm per year, resulting in projected half-lives ranging from 58 years for thin-walled bottles to 1200 years for thick-walled pipes. PET bottles have been found to persist structurally for 15 years or more on the sea bed, in the absence of photo-degradation [13]. These values should be taken with some reserve in that SSDR refers to bulk material degradation and not secondary microfragment production, which can be substantially faster due to surface crazing and the shedding of brittle surface layers under load.

In marine conditions, degradation is slowed by lower temperatures, biofouling, and low oxygen at depth, but accelerated by high surface UV exposure and mechanical stress on buoyant materials. Macro-debris floating in subtropical gyres typically fragments on timescales of years to decades, depending on polymer type and additives.

2.2 Size distribution dynamics and the irreversibility threshold

The usual taxonomy divides marine debris into four sizes, in descending order: macroplastic (>25 mm), mesoplastic (5–25 mm), microplastic (<5 mm), and nanoplastic (usually <1 μm). Studies have consistently shown that the frequency distribution skews heavily to the smaller size ranges, whereas the mass of particles distributes predominantly in the higher categories. Thus, the characterization of the GPGP by Lebreton et al. indicated that microplastics comprised 8% of the total mass but 94% of the particle count [14].

This distribution pattern is due to the unidirectional nature of fragmentation processes, whereby macroplastics generate mesoplastics, which generate microplastics, which generate nanoplastics. Reversal of this cascade is thermodynamically and practically infeasible at ocean scale. Mechanical cleanup remains technically feasible for macroplastics—about 75% of the total mass of debris in the GPGP occurs in items

larger than 5 cm [14]—and has been successfully used to remove hundreds of tonnes of debris from accumulation zones [15]. But cleanup gradually becomes more difficult as the particle size decreases, becoming prohibitive below about 1 mm and effectively infeasible below 100 μm . This size threshold defines the practical irreversibility horizon for marine plastic pollution.

The fragmentation process additionally exhibits a documented mass imbalance: cumulative inputs substantially exceed surface-detectable standing stock, with the difference attributed to vertical mixing, biofouling-induced sinking, beaching, and increasingly to deposition in abyssal sediments and ingestion by biota [3,4,16]. The implication for monitoring is that surface-detectable debris represents only a fraction of the total budget; therefore, any monitoring strategy targeting surface debris must be timed to capture material before it transitions to non-surface compartments.

2.3 Ecological consequences and water-quality endpoints

Once fragmented, the entry of marine plastics into the food web occurs via ingestion by zooplankton and filter feeders, with subsequent transfer through trophic levels having been demonstrated among more than 690 marine species [7]. Ingestion of microplastics has been recorded in commercially harvested fish species across all trophic levels, including in the digestive tract, liver, and muscle tissues of pelagic predator fish relevant to human consumption [17]. Although the bioaccumulation process varies depending on the species and habitats involved and biomagnification through trophic levels remains contested in field research [18], there is now evidence of microplastics in seafood, drinking water, and the human placenta and bloodstream [8, 17, 19-21].

The effects of water pollution go beyond ingestion. Hydrophobic organic compounds and metals are adsorbed by microplastics from the surrounding water, allowing them to act as vectors for further pollutant transfer after ingestion [7]. Leaching of additives in plastics, such as phthalates, bisphenols, and brominated flame retardants, into the surrounding water and into ingesting organisms also occurs [11].

Drinking water is also no exception. Microplastics have been found in tap water samples at up to 628 particles L^{-1} and bottled water samples at up to 4889 particles L^{-1} [20]. Furthermore, a study conducted across nine different countries showed that 93% of bottled water samples contained microplastics [21]. This implies that once plastic debris breaks down to micro-scale, contamination becomes part of the food web and water sources in ways that defeat collection-based remediation. The case for upstream intervention is therefore not preference but necessity.

3 Ocean Dynamics and Debris Accumulation Patterns

3.1 Subtropical gyres as convergence zones

The five subtropical gyres of the world ocean—the North and South Pacific, North and South Atlantic, and Indian—operate as convergence zones for buoyant material through the combined action of three surface-current mechanisms. Ekman transport produces

convergence at gyre centres by deflecting wind-driven flow ninety degrees from the wind direction via the Coriolis force [22]. Geostrophic currents redistribute mass laterally but, being non-divergent, do not themselves contribute to net accumulation [22]. Finally, Stokes drift—the residual mean flow associated with surface gravity waves—adds a wind-aligned component that either enhances or modifies convergence depending on the basin [22,23].

The combination of these processes results in the accumulation patterns described above. In the case of the North Pacific gyre, a convergence pattern exists between latitudes 30° to 40°N and contains the most thoroughly studied accumulation zone on Earth [14]. Similar accumulation zones exist in each of the five gyres, their magnitudes broadly correlating with regional waste input and basin geometry [3,24].

3.2 Windage and differential accumulation

A second-order but operationally relevant factor is the relation between the accumulation pattern and the windage of the debris—the proportion of local wind speed transmitted to a floating object, dependent on its emergent profile [22,23]. Debris of low windage (1–2%; e.g., fishing nets, dense fragments, partially submerged items) follows the Ekman and geostrophic currents closely. Debris of medium windage (~3%; partly filled bottles, foam pieces) experiences additional wind-aligned transport. Debris of high windage (~5%; empty bottles, fishing buoys) deviates substantially from current-only trajectories.

This leads to the conclusion that different types of debris accumulate in spatially distinct sub-regions of each gyre, and that surface-emergent debris is preferentially driven by wind-aligned transport. Objects that are easiest to spot from above the water (bottles, foam, and buoys) are precisely those whose accumulation is most affected by windage, and which will thus accumulate in distinct corridors and downwind margins of the gyre rather than at its geostrophic centre, a partitioning reproduced in windage-resolved transport simulations [22,23].

3.3 The Great Pacific Garbage Patch as case study

Lebreton et al. (2018) provided the most extensive characterization of the GPGP [14]. This investigation showed an area of 1.6 million km² containing 1.8 (1.1–3.6) trillion plastic fragments weighing 79 (45–129) thousand tonnes—four to sixteen times higher than previously reported—where about 75% of the mass is made up of debris larger than 5 cm in size, at least 46% from fishing nets, and microplastics constitute only 8% of the mass but 94% of the total count. Two main properties relevant to the selection of monitoring methods should be mentioned: firstly, that floating plastic debris >5 cm contributes significantly to the mass inventory; and secondly, that concentrations increase exponentially toward the gyre centre, implying that detection-density requirements vary substantially across a single gyre.

3.4 Implications for monitoring strategy

The oceanographic analysis identifies three spatial regimes of operational interest. (i) Convergence-zone interiors—the gyre centres and their immediate surroundings, where buoyant debris accumulates at concentrations several orders of magnitude above ambient background levels. These regions span hundreds to thousands of kilometres in linear extent. (ii) Windrows and convergence front zones—sub-mesoscale frontal structures where Ekman convergence and surface wave action concentrate floating material into linear or rounded patches at the kilometre-to-tens-of-kilometres scale [25]. These structures are ephemeral but recurrent and contain the densest detectable concentrations of buoyant debris. (iii) Source-proximal zones—river plumes, coastal outflows, and downwind populated coastlines where incoming debris flux is highest before transport disperses it [26]. Current collection systems address (i) and (iii); detection systems capable of addressing (ii) and the source-proximal portion of (i) form the missing component, as Section 4 explains quantitatively.

4 Analysis of Existing Monitoring and Removal Approaches

4.1 Satellite remote sensing

Optical sensors in space provide the most realistic technique for global synoptic coverage. One of the best platforms used in this regard is the Multi-Spectral Instrument (MSI) onboard ESA's Sentinel-2, providing 12 spectral bands at resolutions of 10, 20, and 60 metres with revisit times between 2 and 5 days [27]. Macroplastics floating on the sea produce spectral anomalies within the near-infrared and shortwave-infrared bands, which can be exploited through the Floating Debris Index (FDI) and related indices [27,28].

The detection limits are tight. According to Biermann et al., aggregations become detectable only once they occupy at least 30% of a 10 m × 10 m pixel through bottles and bags, or 50% through fishing nets [27]. Below this threshold, the signal-to-noise ratio becomes too low to be useful—roughly translating into approximately 30 m² of contiguous plastic cover per detected pixel, a density rarely encountered outside the densest windrows. Cloud cover further complicates the matter, since the revisit cadence on the order of days does not allow following rapidly changing frontal systems. Furthermore, spectral similarity with seaweed, sea foam, and sun glint creates additional risk of false positives, partially mitigated by machine-learning techniques [28]. In summary, satellite observation allows tracking of large patches, while resolving neither individual items nor small aggregations; most pre-fragmentation debris is undetectable from space.

4.2 River-mouth interception systems

River interceptors collect debris at the boundary between freshwater transport and oceanic input. Deployed Interceptor units incorporate solar-powered conveyor belts

with floating barriers that remove debris prior to discharge [29]. The advantages of river interceptors lie in their operational capacity; they can capture high-concentration debris over a small footprint while being situated upstream of the marine environment entirely. The limitations are equally fundamental. River interceptors are geographically fixed and dedicated to collecting debris from a single river. They cannot address coastal sources downstream of the interception point, offshore inputs, or debris already at sea. Moreover, even where deployed, they are affected by river flow conditions, as heavy rainfalls have repeatedly surpassed the capacities of such deployments [29]. Ultimately, river interceptors tackle the issue of debris inflow and not its subsequent movement and aggregation.

4.3 Manned-vessel cleanup operations

Active offshore systems embody the current state of the art in cleanup. The Ocean Cleanup's System 002 was responsible for collecting about 283 tonnes between 2021 and 2023 across an area spanning 8,352 km² in towed configuration. System 03 extends this with a 2.2 km wing, and modelling suggests that a fleet of approximately a dozen such systems could clean the entire GPGP [15,30]. Their operational strength is collection rather than search: they work effectively in known high-density zones identified through prior modelling, but the cost structure of crewed offshore operations places persistent wide-area patrol outside their envelope. Cleanup of the GPGP at fleet scale is feasible, but persistent monitoring across all five gyres plus accumulation corridors and source-proximal zones at any meaningful cadence is not.

4.4 Aerial and drone surveys

Airborne and UAV imagery offers a resolution between those of satellites and shipboard observation. Both the C-130 missions used in the Lebreton GPGP characterization [14] and UAV missions in coastal regions [31] have been shown to exhibit useful detection capability on macro-debris. The drawbacks are associated with endurance and weather. Small UAVs have a limited range of just hours, while large UAVs may remain airborne only for several days at best; both are weather-sensitive in ways that surface platforms are not; and neither operates persistently at the water surface where buoyant debris actually resides.

4.5 Other monitoring approaches

Several further methods complete the landscape, and each sits at one end or the other of the coverage-resolution plane rather than in its interior. Surface trawls (manta nets) remain the standard for in-situ sampling but cover only narrow transects at the cadence and cost of a host vessel [3]; drifting buoys characterize Lagrangian transport but do not image debris directly; and moored camera systems provide persistent observation only at a single fixed point. Among remote-sensing extensions, aerial hyperspectral imaging improves material discrimination yet remains sortie-limited, while synthetic-aperture-radar (SAR) and thermal-infrared satellite methods see through cloud and darkness but

inherit the coarse pixel scale and non-persistent revisit of spaceborne platforms. None occupies the persistent, item-resolution, intermediate-area regime identified below.

4.6 The spatial-scale gap

Plotting these methods on a coverage-area $\times$ resolution plane shows a clear gap in the middle (Figure 1; the plotted values and their sources are summarized in Table 1). Satellite imagery covers thousands of km² at 10-metre resolution but requires concentrated patches to register. River interceptors operate at point locations with metre-scale resolution. Offshore vessel systems cover thousands of km² at item-scale resolution but only over short campaign windows. Drones and aircraft provide hour-scale visits at sub-metre resolution. The unfilled region—kilometres to tens of kilometres of coverage at item-scale resolution, consistently maintained over weeks to months—is precisely the scale range at which pre-fragmentation debris aggregates into ephemeral but recurrent windrows that satellites miss and offshore systems pass through too rarely to detect. This is the spatial-scale gap that a mobile, autonomous, surface-level platform is uniquely positioned to occupy as a complement to the existing approaches above.

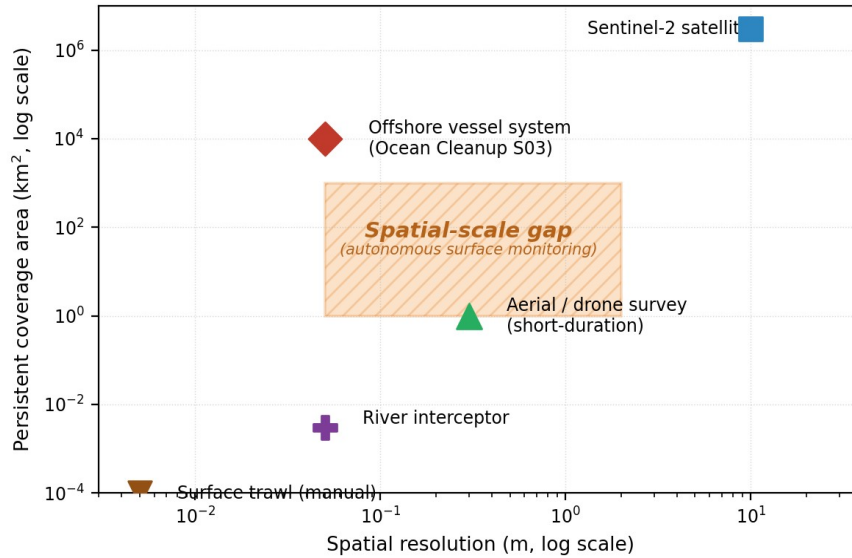


Fig. 1. Spatial-scale gap in marine debris monitoring. Each point represents a representative method for monitoring or removing marine debris in relation to its ability to resolve debris by spatial resolution (x-axis) and to maintain coverage over weeks to months within a certain area (y-axis). The shaded region, covering spatial scales from approximately 0.05 to 2 m resolution and 1 to 1000 km² persistent coverage, falls between satellite and manual or fixed methods and is not addressed by any existing approach. Plotted values and their sources are listed in Table 1.

Table 1. Representative spatial resolution, persistent coverage area, and temporal basis of each monitoring or removal method plotted in Figure 1, with supporting source. Values are order-of-magnitude estimates drawn from the cited literature and from the method descriptions in Sections 4.1–4.5.

Method	Spatial resolution	Persistent coverage	Temporal basis	Ref.
Satellite (Sentinel-2 MSI)	10 m (pixel)	$\sim 10^6$ km ² (synoptic)	2–5 day revisit; not station-kept	[27]
Offshore vessel (Ocean Cleanup S03)	item-scale (≈ 0.05 m)	$\sim 10^4$ km ² per campaign	short campaign windows	[15,30]
Aerial / drone survey	sub-metre (≈ 0.3 m)	~ 1 km ² per sortie	hours of endurance	[31]
River interceptor	item-scale (≈ 0.05 m)	point / fixed ($\sim 10^{-3}$ km ²)	continuous but stationary	[29]
Surface (manual) trawl	net-scale (≈ 0.005 m)	transect ($\sim 10^{-4}$ km ²)	episodic transects	[3]

5 Autonomous Surface Monitoring as an Intervention Strategy

5.1 Requirements derived from the analysis

Contamination pathway analysis (Section 2) and oceanographic analysis (Section 3) together place certain operational requirements on a system designed to address the spatial-scale gap.

Surface-level operation. Buoyant debris is distributed asymmetrically at the air–water interface—bottles stick out above the surface, films lie flat, and fragments hover just below. Detection therefore benefits from sensor lines-of-sight that span this interface from a vantage close to it. Aerial platforms can observe the emergent portion, subsurface platforms the suspended portion, but only surface platforms can observe both.

Pre-fragmentation timing. The system must be capable of operating within the polymer-dependent window during which the debris remains macroscopic (years to decades for floating materials, per Section 2). This timescale sets the monitoring requirement quantitatively: because a floating macroplastic stays detectable for years to decades before fragmenting, a revisit interval of weeks to months is more than sufficient to intercept it pre-fragmentation. The binding constraint is therefore not revisit frequency but sustained presence—the platform must remain on-station across that cadence—which necessitates persistent rather than episodic operation and rules out short-endurance aerial surveys.

Multi-modal sensing for natural-feature discrimination. Natural surface features (algae, sea foam, sun glint, biological congregation zones) generate signatures that overlap with those of debris [27]. Multi-modal sensing is necessary to discriminate between them.

Intermediate-scale persistent coverage. The spatial-scale gap discussed in Section 4 maps to coverage at the intermediate scale (kilometres to tens of kilometres maintained over weeks to months)—the operating envelope of small autonomous surface vehicles, not large crewed ships or short-endurance aircraft.

Mobility responsive to convergence dynamics. Because windage disperses debris classes across sub-regions and windrows are ephemeral (Section 3.2), monitoring must be repositionable in response to oceanographic forecasts, not stationary.

5.2 Ocean Voyager: a prototype implementation

Ocean Voyager is an affordable autonomous surface vehicle developed to meet the above requirements. It is a catamaran-hulled platform whose twin-hull configuration provides the lateral stability needed for reliable sensing; propulsion is by differential twin thrusters, an embedded single-board computer runs the perception and autonomy software, and a battery-based power system supports solar recharging for extended endurance. Sensing is staged: a servo-mounted thermal camera performs a 360° panoramic scan to propose candidate anomalies, after which bow-mounted RGB cameras confirm detections within near-range fields of view using an on-board object detector and multi-camera voting. It navigates autonomously between waypoints and returns data to a base station when detection events occur. The perception component has been validated on representative marine imagery and the autonomy controller under software-in-the-loop simulation; detailed platform metrics—physical dimensions, endurance, speed, and effective detection range—together with detector-performance evaluation are reported in dedicated engineering work and fall outside the scope of this analytical paper. Its significance here lies in its role as evidence that the requirement set can be fulfilled within a cost profile consistent with multi-unit deployment, rather than as the central contribution of this paper.

In these respects Ocean Voyager occupies the sub-metre-resolution, kilometre-to-tens-of-kilometres coverage region of Figure 1: its surface-level operation captures the air–water interface that satellite and subsurface methods miss, its multi-modal sensing addresses natural-feature discrimination, and its autonomous repositioning supports deployment responsive to convergence-zone forecasts.

5.3 Multi-vehicle deployment as a scaling response

The single-vehicle envelope of any platform in the spatial-scale gap is, by definition, far smaller than the relevant accumulation regions: the GPGP alone covers 1.6 million km², and monitoring across all five basins exceeds ten million km². Persistent monitoring at this scale is therefore inherently a multi-vehicle problem.

This reasoning leads us to a fleet-based deployment architecture in which multiple autonomous surface vehicles cooperatively divide the target area, exchange detection data through a shared base station and inter-vehicle relays, and reposition to emerging accumulation zones identified through the gyre-transport dynamics discussed in Section 3. Such an architecture has precedent, as seen with USV swarms for aquaculture monitoring [32] and cooperative coverage [33].

The oceanographic analysis provides a deployment template: platforms deployed along convergence corridors identified through Ekman–Stokes modelling, downwind margins of gyre centres where high-windage objects accumulate, and river-plume and coastal-outflow boundaries that complement fixed river interceptors with mobile offshore detection. Coordination poses non-trivial challenges—communication latency, energy management under intermittent solar charging, and fault tolerance under wave loading—but these are addressable with existing autonomous-systems methods.

This deployment architecture is an analytically motivated concept derived from the spatial-scale mismatch between single-vehicle range and ocean-scale accumulation, not an implemented system; no swarm deployment has been simulated or fielded as part of this work.

6 Discussion

6.1 The analytical case

The approach put forth here treats marine plastic monitoring as a spatial-scale problem rather than a technology-acquisition one, and the resulting prescription is testable: if the gap is real, the residual undetected debris budget should match the size and density signature—surface-emergent, item-scale, concentrated in ephemeral windrows—that the gap leaves uncaptured by satellite and offshore-vessel methods.

6.2 Limitations

Three aspects of the current analysis merit explicit discussion. First, the prototype used to motivate the requirements analysis has not yet been field-deployed; the analysis is predictive about the behaviour of systems in the gap, and observational confirmation awaits open-water trials. Second, the environmental analysis draws on existing literature rather than new field measurements; although the cited oceanographic and degradation-rate studies are well established, integrating them into a monitoring-gap argument is more a matter of synthesis than of primary research. Finally, the multi-vehicle deployment idea is developed analytically but not implemented; the claim that it is the natural response to the spatial-scale mismatch is purely an analytical one.

Indeed, field data could feed back into the analysis itself in order to hone and refine its predictions: detection-rate data could narrow the missing-plastic budget [4,16], and spatial-pattern data could test the windage and windrow predictions of Section 3.

7 Conclusions

The problem of marine plastics requires action prior to fragmentation, since microplastics are practically impossible to retrieve once formed. Polymer-specific degradation kinetics define the pre-fragmentation period of time, while oceanographic

dynamics determine where and on which spatial scale monitoring needs to take place during this period. Current solutions address scales smaller than metres and greater than kilometres, leaving the middle ground without a solution. Autonomous surface vehicles, operating at the air–water interface with multi-modal sensing and repositioning capabilities, fill this gap as a complement to existing approaches; field deployment of single units, and eventual coordinated fleets, are the obvious next steps.

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