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# From producer attribution to governance: Quantifying responsibility concentration in marine plastic pollution

Nelson Rangel-Buitrago and Alex Paternina-Ramos

Universidad del Atlantico, Colombia

## Research Article

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**Corresponding author:**
Nelson Rangel-Buitrago;
Email: nelsonrangel@mail.uniatlantico.edu.co

## Abstract

Extended Producer Responsibility (EPR) requires quantitative tools to identify responsibility concentration and prioritize interventions. This study introduces an inequality-based framework combining Lorenz curves, Gini coefficients, and concentration ratios to assess producer responsibility in marine plastic pollution. We analyzed 232 producer-attributable items from 830 macrolitter items collected on Isla Arena, an uninhabited Colombian Caribbean island, identifying 48 producers, 72 brands, and 95 products. A Corporate Environmental Impact (CEI) index assessed whether abundance-based dominance corresponded to potential environmental impact. Producer responsibility was highly concentrated (Gini = 0.690; bootstrap 95% CI: 0.629–0.698), with the five and ten leading producers accounting for 65.5% and 80.6% of attributable litter, respectively. Beverage companies dominated, while Pony Malta alone represented 27.2% of attributable items. Impact-based inequality was nearly identical (Gini = 0.692). Sensitivity analysis addressing the 72.0% unattributed fraction showed that category-specific attribution corrections increased inequality (Gini = 0.714), supporting the robustness of observed concentration. These findings establish responsibility inequality as a measurable property of pollution assemblages and provide a transferable framework for targeting EPR interventions, assessing governance feasibility, and monitoring corporate environmental performance across pollution systems.

## Impact statement

This study introduces responsibility inequality as a new and measurable dimension of marine plastic pollution. By applying Lorenz curves, Gini coefficients and concentration ratios to a producer-attribution dataset from a remote Caribbean island, the research demonstrates that plastic pollution responsibility is highly concentrated among a small number of corporate actors rather than being broadly distributed across the marketplace. Five beverage producers accounted for nearly two-thirds of all attributable litter, while responsibility and environmental impact exhibited almost identical concentration patterns. The framework advances producer-attribution studies beyond the identification of responsible companies by quantifying how responsibility is distributed among them, a distinction directly relevant to environmental governance because concentration determines whether interventions can be directed towards a limited number of actors or require system-wide approaches. Because the approach is transparent and directly applicable to existing producer-attribution datasets worldwide, and because the data and code are released openly, it offers a practical framework, ready for multi-site validation, for linking corporate accountability, environmental monitoring and evidence-based plastic pollution governance.

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## Highlights

- Producer responsibility inequality can be quantified using Lorenz–Gini metrics
- Responsibility concentration provides a diagnostic of governance tractability
- Five producers accounted for 65.5% of attributable plastic litter
- Abundance and impact concentration showed near-perfect correspondence
- Concentration is robust to bootstrap resampling and to attribution bias
- High-Gini systems are particularly suitable for targeted EPR measures
- The framework transforms producer attribution into a governance tool

## Introduction

Marine plastic pollution research has moved through three successive questions. The first asked how much, quantifying densities and accumulation rates along beaches (Rangel-Buitrago, 2025a), the sea surface (Schmid et al., 2021) and the seafloor (Madricardo et al., 2020). The

second asked what, resolving assemblages into standardised categories through instruments such as the OSPAR protocol (Cesarano et al., 2023) and the Joint List of Litter Categories (Fleet et al., 2021). A third question now emerges: who is responsible, and how is responsibility distributed (Brabo et al., 2024, 2026)?

The question reflects a broader shift in environmental governance (Hickle, 2014). Plastic pollution was traditionally framed as a waste-management problem, placing responsibility on consumers and municipalities (Williams and Rangel-Buitrago, 2019). More recently, Extended Producer Responsibility (EPR), deposit-return systems and the negotiations towards a global plastics treaty have recognised producers' role in shaping material flows through design, packaging and distribution (Vince and Hardesty, 2017), driving brand-audit studies that link litter to specific actors (Ryan et al., 2026).

Part of this literature has already moved beyond simple presence. In the most comprehensive global assessment to date, Cowger et al. (2024) ranked companies by their share of branded items across 1,576 audit events, plotted cumulative share against the number of companies responsible for it, and reported the minimum number of companies accounting for half of the global branded load (56 companies; top five = 24%). That analysis established at global scale that branded pollution is dominated by a limited set of consumer-goods producers, and is the direct antecedent of the present work. What it did not do, and what remains generally absent from marine-litter research, is express that dominance as a formal, bounded and scale-invariant measure of the distribution as a whole: cumulative curves and top-k counts describe the upper tail, but do not summarise the full distribution in one statistic that, at similar detectable producer richness, can be compared across sites of very different size, nor separate assemblages with identical top-five shares but very different tails.

The distinction matters because the governance response depends on it: a stream generated evenly by hundreds of producers calls for market-wide instruments, whereas one dominated by a handful is far more tractable (Miles et al., 2001; Williams and Rangel-Buitrago, 2019). The missing measurement is inequality, which has a mature, scale-invariant toolkit in economics built on the Lorenz curve and Gini coefficient (Siddiq et al., 2023; Tobias et al., 2024).

Isla Arena, on the central Caribbean coast of Colombia, offers an unusually "clean" setting for that measurement: a small, uninhabited carbonate cay barely a metre above sea level, with no resident population and no local waste-generating activity, whose low, overwash-prone morphology makes it a convergence and retention zone for litter delivered by regional currents, winds and episodic events (Rangel-Buitrago et al., 2019; Rangel-Buitrago, 2025a; Rangel-Buitrago et al., 2026). Because nothing is discarded there, its litter carries no local-disposal signal.

The present study re-analyses the producer-attributable fraction of that assemblage, previously classified by Rangel-Buitrago et al. (2026). The relationship between the two papers should be stated plainly. The earlier paper introduced the Taxonomy-inspired Hierarchical Classification of Plastic Litter (THCPL) and the Corporate Environmental Impact (CEI) index and used them to report which producers, brands and products were present and in what numbers; its object was the classification system and the inventory it generates, and it reported no inequality statistic. The present paper takes that inventory as input and asks a different question: what is the shape of the responsibility distribution, is it robust to the large unattributed fraction and what does that shape imply for the choice of governance instrument? Its contributions are the transfer of Lorenz–Gini methodology into producer-responsibility assessment, the demonstration that abundance- and impact-based concentration converge, a quantitative treatment of attribution bias and the reading of the coefficient as a diagnostic of governance tractability.

## Inequality of imported responsibility

The term *producer assemblage* refers to the distribution of attributable litter items among the producers at an accumulation site (Rangel-Buitrago et al., 2026). Like a biological assemblage of species and individuals, it consists of producers and their item abundances. Three of its properties are easily confused but distinct: richness, the number of producers; dominance, how far a few stand above the rest; and inequality, the shape of the whole distribution. Item counts (Shumway and Ward, 2025), producer lists (Brabo et al., 2024) and category inventories (Fleet et al., 2021) capture richness and some dominance, but not inequality, the property the Lorenz curve and Gini coefficient measure.

The Gini coefficient is a widely used inequality measure in economics and the social sciences (Muñoz et al., 2026). Unlike diversity indices, it focuses on the distribution of shares among contributors (Charles et al., 2022), gauging departure from equality independently of assemblage size, though not of the number of contributors observed (Gavilan-Ruiz et al., 2024). Two assemblages may each hold ten producers and one hundred items, yet in one every producer contributes ten while in the other a single producer contributes fifty; both share richness and abundance, but only the Gini coefficient separates them, and interventions depend less on how many actors are present than on how responsibility is shared among them (Faibil et al., 2023). The Lorenz curve represents the same information graphically (Rousseau et al., 2018), plotting the cumulative share of items against that of producers ordered from least to most abundant: under equality it follows the 45° line, and as contributions concentrate it bows downward, a departure the coefficient summarises from 0 to near 1 (Blesch et al., 2022).

Applying these metrics to pollution requires an inversion. In economics they assess desirable goods such as income, where inequality is undesirable (Gavilan-Ruiz et al., 2024); in pollution the distributed quantity is a load, so a high producer Gini means responsibility is concentrated among few actors – from a governance view an opportunity, since interventions can target a limited set of producers influencing much of the stream (Williams and Rangel-Buitrago, 2019, 2022). This aligns with the polluter-pays principle and with EPR (Wiesmeth, 2021; Gaur et al., 2022), making the coefficient a governance indicator rather than a purely statistical descriptor.

Scale invariance suits the approach to remote sites such as Isla Arena: describing a distribution's shape rather than its magnitude, the coefficient stays meaningful even when only part of an assemblage is attributable. Here producer information was available for 232 of 830 items (28.0%), so all statistics reported below are conditional on the attributable pool; how far they extend to the whole assemblage is examined in the sensitivity analysis.

## Methods

### *Study area*

Isla Arena is a small, uninhabited island in the central Colombian Caribbean Sea (Bolívar Department) at approximately 10°44′20.83″

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N and 75°21′03.35″ W (Figure 1). It covers 779 $m^2$, has a perimeter of approximately 213 m and rarely exceeds 1 m above mean sea level. Its low-lying, overwash-prone morphology favours the trapping and retention of floating debris transported by regional oceanographic processes (Rangel-Buitrago et al., 2017, 2018).

Geomorphologically, it is the emergent portion of a dormant carbonate bank associated with mud-diapir activity along the central Colombian Caribbean margin (Bosence, 2005; Gracia et al., 2012), surrounded by shallow carbonate environments including seagrass beds and coral assemblages (Pinzón et al., 1998) whose ecological importance heightens the relevance of accumulated litter.

The island lies in a microtidal environment with mixed semi-diurnal tides rarely exceeding 70 cm (Rangel-Buitrago et al., 2017, 2018). Waves are dominated by northeast-generated swells, with mean significant heights near 1.7 m and peak periods near 7.3 s (Gracia et al., 2018a), and longshore transport is predominantly southwestward with seasonal reversals during the rainy season (Anfuso et al., 2015).

Although uninhabited and free of local waste generation, the island is embedded within a densely populated, economically active coastal region shaped by urban centres, maritime transport, fisheries and tourism, so all accumulated litter is externally sourced and delivered through regional circulation pathways and episodic meteorological events (Rangel-Buitrago et al., 2017). This absence of local disposal, combined with the island's capacity to retain drifting debris, makes it a suitable natural laboratory for evaluating imported producer responsibility.

## Dataset and analytical design

The analysis used the macrolitter dataset previously reported for Isla Arena by Rangel-Buitrago et al. (2026; Supplementary Material S1): 830 litter items (>25 mm) collected across the island and classified with the THCPL, which nests items into seven levels: Phylum (material), Class (use category), Order (item type), Family (producer), Genus (brand), Species (product) and Origin (country).

Of the 830 items, 232 (28.0%) retained sufficient diagnostic information for attribution to a specific producer, representing 48 Families (producers), 72 Genus (brands) and 95 Species (products); the remainder were excluded, so all calculations describe the attributable producer assemblage rather than the total litter load. Within the THCPL framework the Family level corresponds to the corporate producer responsible for manufacturing, distributing or

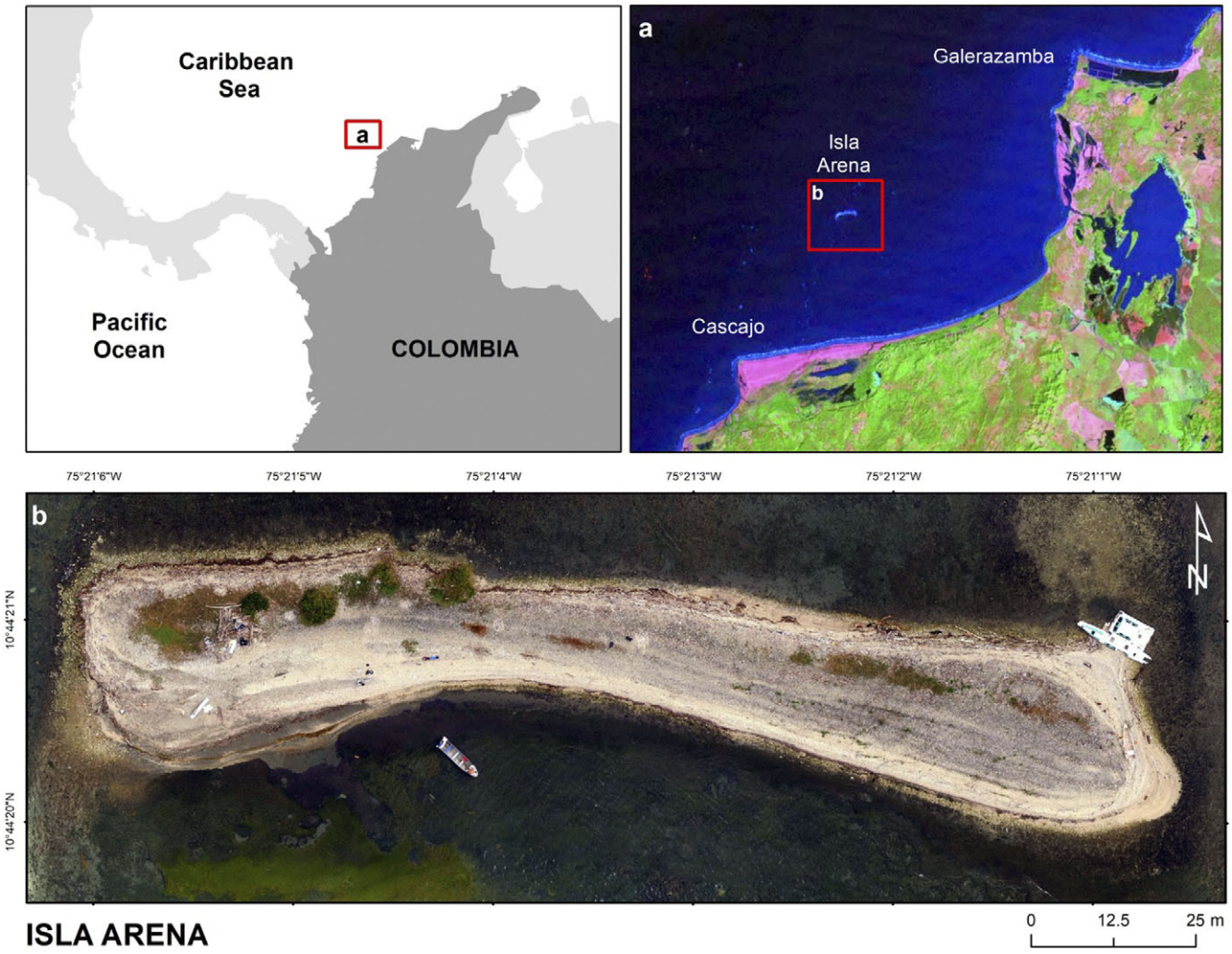



**Figure 1.** Study area and geographic setting of Isla Arena, Colombian Caribbean Sea. (a) Location of Isla Arena within the central Colombian Caribbean coast. (b) High-resolution aerial image of the island showing its elongated carbonate morphology, low elevation, and isolation from mainland sources. Despite its small size (779 $m^2$) and absence of permanent human occupation, the island functions as a regional accumulation sink for marine litter transported through coastal circulation pathways.

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marketing a product, and families were the analytical unit throughout. Assignments relied solely on identifiable markings such as company names, logos, trademarks and labels; items with incomplete or ambiguous markings were classified as unattributable, prioritising certainty over sample size so that metrics reflect only verifiable producer-responsibility relationships (Brabo et al., 2024). No resin identification was performed, so items are described by form (plastic bottles, caps, films) and never by polymer type.

Geographic origin was assigned at the product level and independently of the brand owner's nationality, from the country of manufacture, bottling or distribution declared on the item itself: the statutory "manufactured/bottled by" legend, the responsible-importer address or, where legible, the GS1 prefix of the printed barcode. Where a label identified a national bottler or licensee, origin followed that company rather than the parent corporation, so items filled by Panamanian bottlers were assigned to Panama irrespective of where the trademark is held. Origin is an attribute of the packaging encountered, not an inference from the brand.

Producer inequality was evaluated with Lorenz curves built from family-specific item abundances: families were ranked in ascending order and cumulative family and item shares calculated across the ranked distribution, departures from the 45° line indicating increasing concentration. Inequality was quantified with the Gini coefficient (Gini, 1936; Giorgi and Gigliarano, 2017), from the standard mean-difference formulation:

$$G = \frac{2}{n\sum_{i=1}^{n} x_i}\left(\sum_{i=1}^{n} i x_i\right) - \frac{n+1}{n}$$

where $x_i$ is the abundance of the $i$-th family after ascending ranking and n is the total number of families, the coefficient ranging from 0 (perfect equality) to values approaching 1. Concentration ratios (CR1, CR3, CR5, CR10) were also calculated as the cumulative share contributed by the one, three, five and ten most abundant families; whereas the Gini coefficient characterises inequality across all families, these ratios capture upper-tail dominance.

Because abundance need not reflect ecological consequences, a secondary analysis applied the CEI metric of Rangel-Buitrago et al. (2026), which combines the number of items attributed to a producer with the hazard and mobility scores of the item types that producer contributed, and is defined for each family j as:

$$\mathrm{CEI}_j = N_j \underset{j}{h}\, \underset{j}{m}$$

where

$$\underset{j}{h} = \frac{1}{N_j}\sum_{i=1}^{N_j} h_i$$

and

$$\underset{j}{m} = \frac{1}{N_j}\sum_{i=1}^{N_j} m_i$$

Thus, the complete formulation can be presented compactly as:

$$\mathrm{CEI}_j = N_j\left(\frac{1}{N_j}\sum_{i=1}^{N_j} h_i\right)\left(\frac{1}{N_j}\sum_{i=1}^{N_j} m_i\right)$$

where $N_j$ is the number of items attributed to family $j$, and $h_i$ and $m_i$ are the hazard and mobility scores (both bounded 0–1) assigned to item i from its THCPL item type following Rangel-Buitrago et al. (2026); hazard reflects the potential of an item type to cause harm, and mobility its propensity to be transported at sea. The relative impact of a producer is $\mathrm{CEI}_j/\Sigma$ CEI, and the assemblage hazard index (AHI) is the item-weighted mean of $h_i$. Gini coefficients were computed for both distributions and compared; CEI is a secondary interpretive layer, not a measurement of realised ecological damage.

Four procedures tested robustness. First, sampling uncertainty was quantified by resampling the 232 attributable items with replacement (10,000 replicates, fixed seed) and recomputing every statistic (Efron and Tibshirani, 1993). Second, differential loss of traceability was addressed by calculating the attribution success rate of each THCPL Order and re-weighting each attributed item by the inverse of the attribution probability of its own category, so that categories losing labels faster are not under-represented. Third, the unattributed fraction was bounded explicitly: writing α for the proportion of unattributed items belonging to producers already present in the identifiable pool, the remaining $(1-\alpha)$ were assigned to previously unseen producers either as single-item producers (maximal dispersion) or reproducing the observed rank-abundance shape (structured dispersion), across α from 1 to 0, with an upper bound assigning all unattributed items to the leading producer and a scenario setting unseen richness from the Chao1 estimator (Chao, 1984) (full definitions in Supplementary Material S2). Fourth, the dependence of the coefficient on producer richness was examined by rarefaction: the attributable items were sub-sampled without replacement to 25–200 items (2,000 subsamples per size) and the Gini coefficient recomputed against the number of producers observed in each subsample. All analyses were performed in Python; code, item-level data and intermediate results are provided as Supplementary Materials S1–S3.

## Results and discussion

### *Characteristics of the Isla Arena macrolitter assemblage*

A total of 830 macrolitter items were recorded across the 779 $m^2$ surface (mean density 1.07 items $m^{-2}$), all exceeding 25 mm and spread across shoreline, supratidal and interior sectors. Densities were comparable to other island settings worldwide, including the Gulf of Aqaba (Al-Najjar and Al-Shiyab, 2011), the Azores (Ríos et al., 2018), Trindade Island (Andrades et al., 2018) and the Cocos (Keeling) Islands (Lavers et al., 2019), though comparisons require caution given differences in sampling design and reporting.

At the highest THCPL levels the assemblage was entirely Phylum Litter ($n$ = 830; Figure 2). Plastics dominated material composition (798 items; 96.1%), followed by glass (23; 2.8%) and metal (9; 1.1%). At the Order level, rigid plastics dominated (757; 91.2%), followed by foams (29; 3.5%), glass bottles (23; 2.8%), composites (9; 1.1%), aerosols (6), caps (3), cans (2) and non-rigid plastics (1).

Finer taxonomic resolution revealed greater complexity: 48 Families (producers), 72 Genus (brands) and 95 Species (products). Producer-level attribution was possible for 232 items (28.0%), while 598 (72.0%) lacked diagnostic information owing to degradation, abrasion, fragmentation, biofouling or label loss. Functionally, 198 of the attributable items (85.3%) were beverage-related, and 191 (82.3%) were plastic beverage bottles, against 34 non-beverage items (14.7%) spanning household, personal-care, medical, food and engine-maintenance products (Figure 3).

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### Corporate dominance patterns: Leading producers

The producer-attributable assemblage was strongly hierarchical, with a few dominant contributors and a long tail of low-frequency producers. Bavaria–Anheuser-Busch InBev ranked first with 64 items (27.6%; Table 1, Figure 3), followed by AJE Group (26; 11.2%), Postobón S.A. (22; 9.5%), PepsiCo (20; 8.6%) and The Coca-Cola Company (20; 8.6%), together 152 of 232 items (65.5%). Responsibility accumulated rapidly: the three leading families reached 48.3% and the ten leading families 80.6% (Table 1), while the remaining 38 families contributed only 45 items (19.4%). The asymmetry was sharpest at the lower end, where 31 of the 48 families (64.6%) were represented by a single item. Half of the attributable load was reached with only four producers; the equivalent figure in the global compilation of Cowger et al. (2024) is 56 companies, an indication of how much more concentrated a regional sink can be than the worldwide aggregate.

The dominant group was homogeneous: all five leading families are beverage companies – two multinationals, one global brewer through its regional subsidiary and two major Latin American firms. Producer concentration was thus accompanied by functional concentration, beverage packaging being the principal pathway for identifiable litter.

Dominance was reinforced at brand level (Genus; Figure 3). Pony Malta alone accounted for 63 items, 27.2% of the assemblage and 98.4% of all items assigned to Bavaria–Anheuser-Busch InBev, followed by Big Cola (18), Gatorade (15), Coca-Cola (13) and the bottled waters Glacial and Cristal (10 each); the five leading brands reached 51.3%, while 59 of the 72 brands (81.9%) were represented by two items or fewer. Dominance therefore arose not from broad portfolios but from a few highly successful brands, making the signal not merely beverage-dominated but, to a notable degree, single-brand dominated – consistent with the global prevalence of plastic beverage containers in coastal macrolitter (González-Fernández et al., 2021; Garces-Ordoñez et al., 2025a; Kelly et al., 2026).

Geographic attribution was similarly concentrated: of the 232 attributable items, 224 (96.6%) carried a Colombian origin declaration, with only eight from Panama (6), Guatemala (1) and Thailand (1). Despite the island's offshore position, the assemblage reflects a predominantly domestic production–consumption system, with three nested forms of concentration: a few dominant producers, fewer dominant brands and a predominance of beverage products (Figure 3).

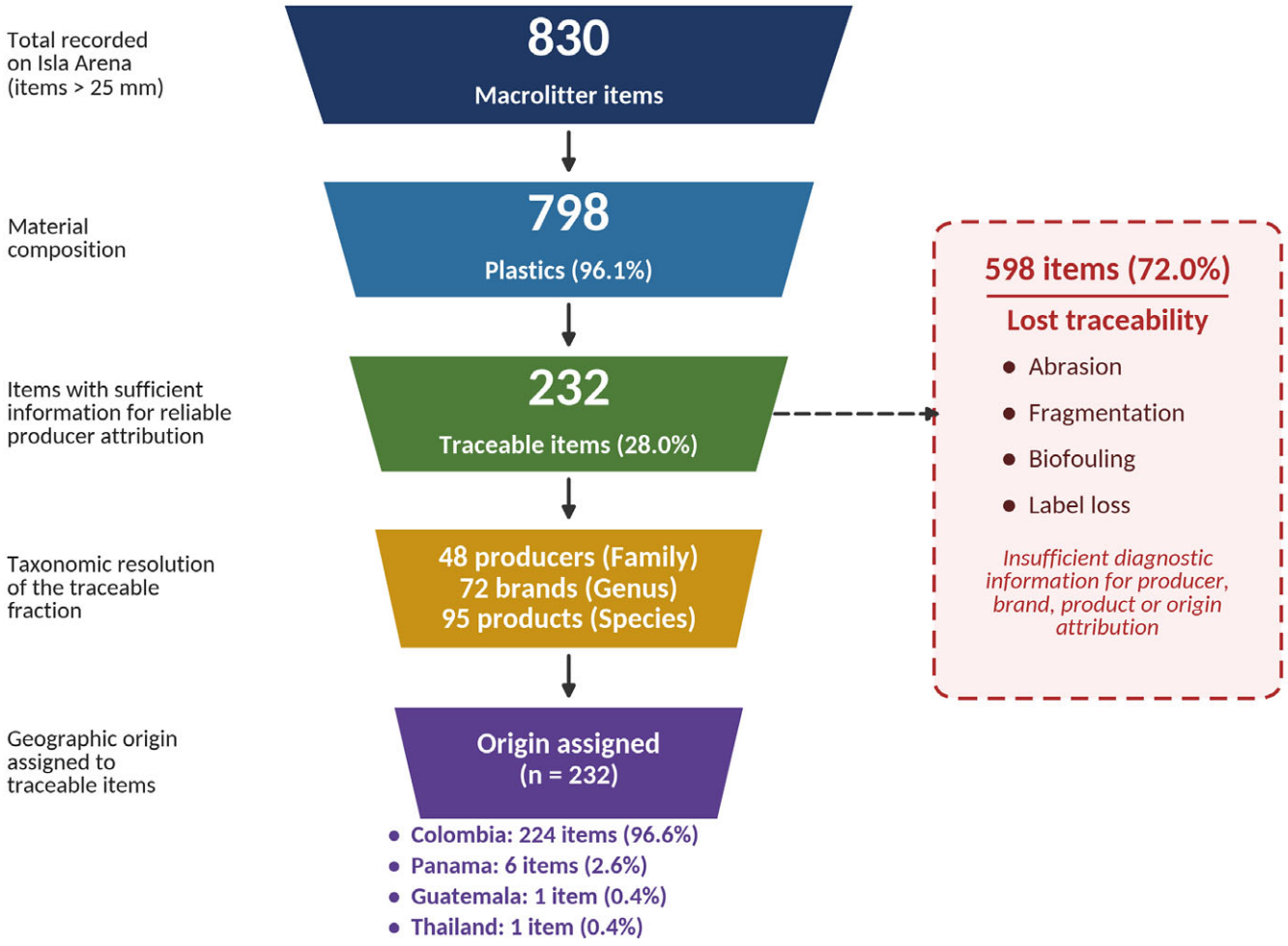



**Figure 2.** Traceability funnel of the Isla Arena macrolitter assemblage. Of the 830 macrolitter items recorded on the island, 798 (96.1%) were plastics, but only 232 items (28.0%) retained sufficient information for reliable producer attribution. The remaining 598 items (72.0%) lost traceability through abrasion, fragmentation, biofouling and label loss. The traceable fraction contained 48 producers (Families), 72 brands (Genus) and 95 products (Species).

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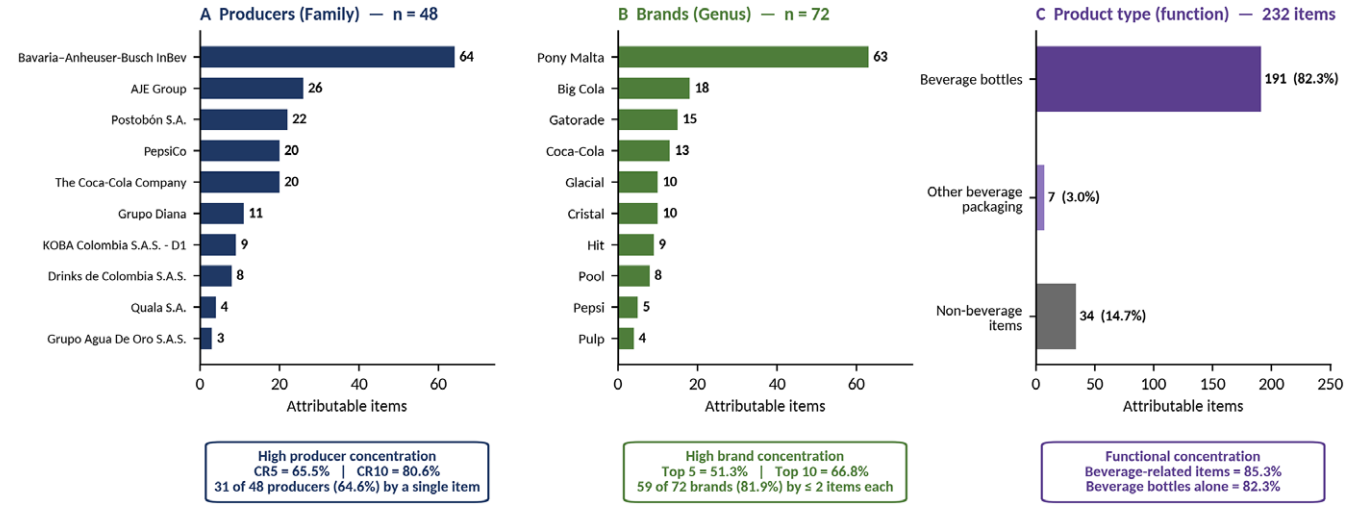



**Figure 3.** Concentration across the producer, brand and product dimensions of the attributable assemblage. (a) The ten leading producers; the five leading account for 65.5% of attributable items, and 31 of the 48 producers are represented by a single item. (b) The ten leading brands; the five leading account for 51.3%, and 59 of the 72 brands are represented by two items or fewer. (c) Functional composition: 85.3% of attributable items are beverage-related, and 82.3% are plastic beverage bottles. The functional classification is rule-based and reproducible from the code in Supplementary Material S3.

**Table 1.** Leading producers of the Isla Arena attributable assemblage, with item counts, item share and cumulative share

| Rank | Family/producer | Items (*N*) | Share (%) | Cum. share (%) |
|---|---|---|---|---|
| 1 | Bavaria – Anheuser-Busch InBev | 64 | 27.6 | 27.6 |
| 2 | AJE Group | 26 | 11.2 | 38.8 |
| 3 | Postobón S.A. | 22 | 9.5 | 48.3 |
| 4 | PepsiCo | 20 | 8.6 | 56.9 |
| 5 | The Coca-Cola Company | 20 | 8.6 | 65.5 |
| 6 | Grupo Diana | 11 | 4.7 | 70.3 |
| 7 | KOBA Colombia S.A.S. – D1 | 9 | 3.9 | 74.1 |
| 8 | Drinks de Colombia S.A.S. | 8 | 3.4 | 77.6 |
| 9 | Quala S.A. | 4 | 1.7 | 79.3 |
| 10 | Grupo Agua De Oro S.A.S. | 3 | 1.3 | 80.6 |
| – | Remaining 38 producers | 45 | 19.4 | 100.0 |
| | TOTAL (48 producers) | 232 | 100 | – |

*Note:* The top five producers, all beverage companies, account for 65.5% of attributable items.

## Lorenz curve of producer responsibility

The Lorenz curve shows how producer responsibility is distributed (Figure 4). Rather than following the line of equality, it is pronouncedly concave, a flat-then-steep geometry signalling strong concentration and the graphical form of the dominance hierarchy described above.

This reflects the imbalance between richness and responsibility (Figure 5). Of 48 families, 31 (64.6%) were single-item and together held only 13.4% of attributable litter; a further 12 contributed two to nineteen items (49 items, 21.1%); and just five (10.4%) contributed 152 items, or 65.5% of the load. Richness was thus largely decoupled from influence. This is fundamental for interpreting attribution datasets: many families may be present, suggesting a diffuse source, but most contribute marginally while a small subset dominates, so richness is not evidence of shared responsibility (Boucheron et al., 2004).

Accordingly, the curve rises very slowly across the first 70–80% of the distribution, an extended flat stretch where richness far exceeds influence, then changes abruptly as the dominant beverage families enter and it climbs steeply towards unity. This transition from a broad low-contribution tail to a narrow high-contribution apex is the assemblage's defining feature.

The cumulative-contribution curve (Figure 6) shows the same pattern by rank: the leading producer reaches 27.6% (CR1), the top three 48.3% (CR3), then CR5 = 65.5% and CR10 = 80.6%, after which it approaches an asymptote – an assemblage in which apparent diversity masks substantial inequality of responsibility.

## The Gini coefficient and the abundance–impact coupling

Whereas the Lorenz curve is graphical, the Gini coefficient reduces the distribution to one value (Gini, 1936). For Isla Arena the abundance-based coefficient was 0.690 (Table 2); values near 0.70 typify strongly concentrated systems where a small subset holds most of the load. The concentration ratios reinforce this: fewer than a quarter of producers account for over four-fifths of attributable litter.

The principal finding arose when contributions were weighted by potential impact using the CEI index. The impact-based Gini was 0.692, just 0.002 above the abundance-based value (Table 2; Figure 7), and the two rankings were strongly correlated (Spearman $\rho = 0.86$). This near-perfect correspondence means the producers contributing the most items also contribute the greatest potential impact.

This contrasts with heterogeneous assemblages, where abundance and impact may fall on different producers because some contribute few items but carry high hazard or mobility. On Isla Arena, dominated by plastic beverage bottles (Figure 7), similar hazard and transport traits (mean AHI 0.754; mean mobility 0.594) leave the weighting little to differentiate, so impact tracks abundance closely.

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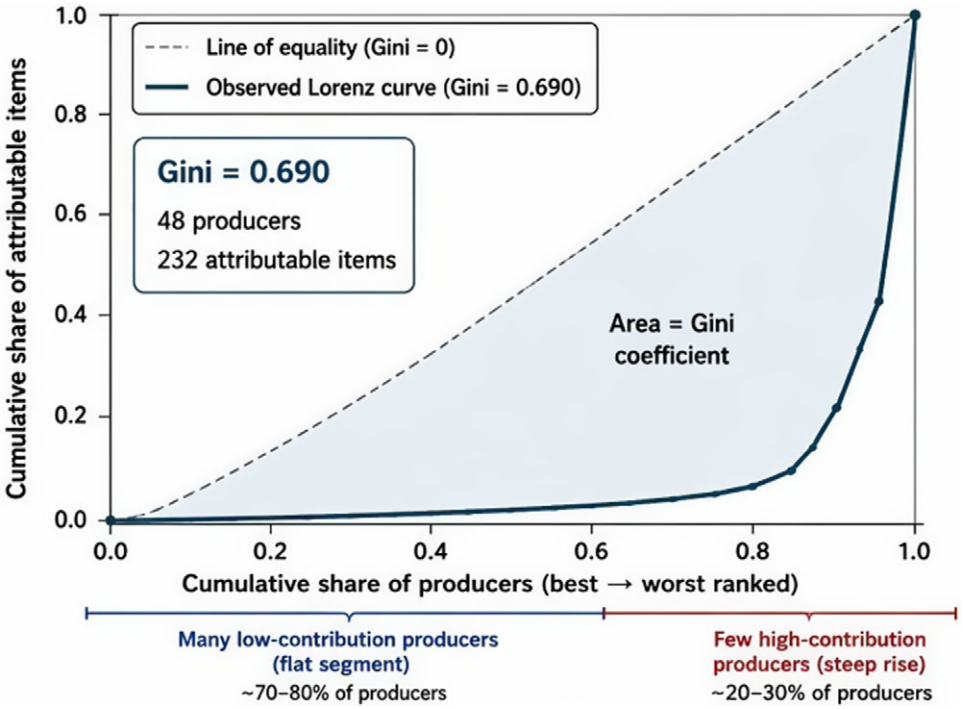



**Figure 4.** Lorenz curve of producer responsibility for the Isla Arena assemblage. The observed Lorenz curve departs strongly from the line of equality, indicating a highly unequal distribution of responsibility among producers. The characteristic flat-then-steep geometry reflects the coexistence of many low-contribution producers and a small number of dominant contributors. The resulting Gini coefficient of 0.690 indicates strong producer concentration.

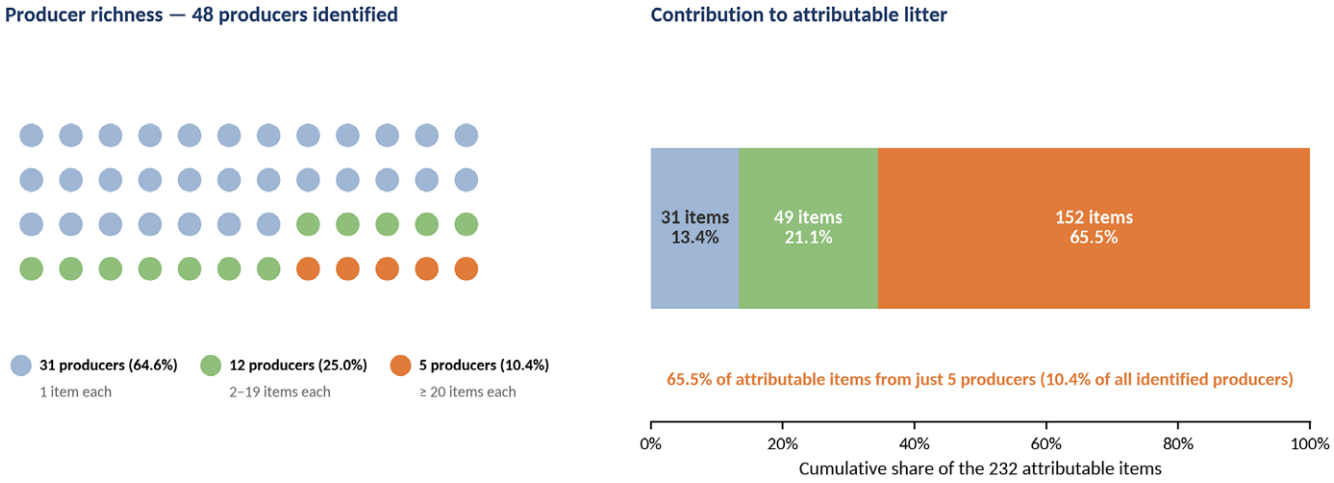



**Figure 5.** Relationship between producer richness and producer responsibility within the attributable assemblage. Although 48 producers were identified, responsibility was distributed highly unevenly: 31 producers (64.6%) contributed a single item each and only 13.4% of attributable litter, 12 producers (25.0%) contributed between two and nineteen items (21.1%) and five producers (10.4%) accounted for 152 items, or 65.5% of all attributable items. The figure shows the decoupling between producer richness and producer influence.

Two consequences follow. First, in functionally simplified systems abundance-based metrics alone reliably approximate responsibility concentration, and the more assumption-dependent hazard weighting adds little, being most informative where item types and impact profiles are more varied. Second, the coupling sharpens the governance signal: because responsibility and impact converge on the same actors, the usual trade-off between tractability and urgency is largely absent, and interventions on the dominant beverage producers would address both the quantity of litter and most of its estimated ecological load (von Philipsborn et al., 2019; Sovacool et al., 2021).

### Robustness of the concentration estimate

Because 72.0% of the assemblage could not be attributed, the reported concentration could in principle be an artefact of who loses their label first. Durable rigid packaging carrying embossed or printed corporate marks may survive weathering better than thin

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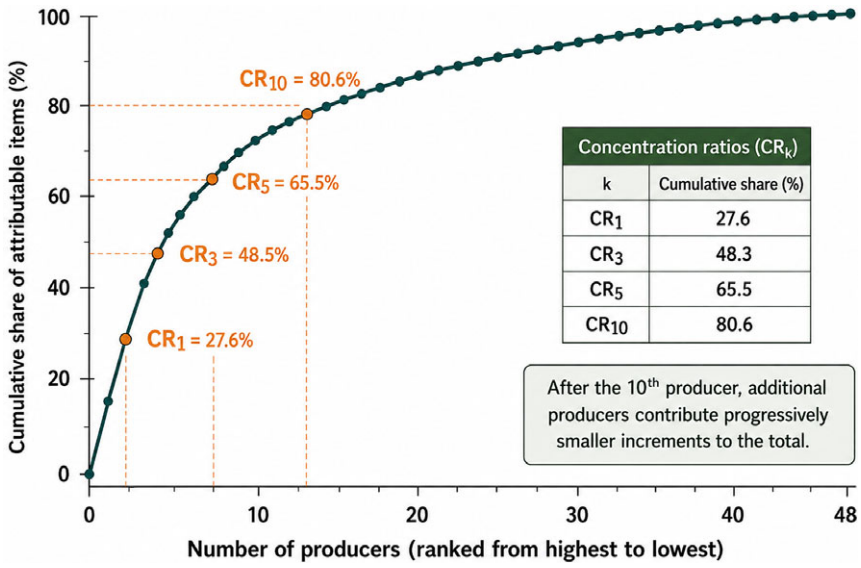



**Figure 6.** Cumulative contribution of ranked producers (families) and concentration ratios (CRk). Responsibility accumulates rapidly among the highest-ranked producers: the leading producer accounts for 27.6% of attributable litter (CR1), the top three for 48.3% (CR3), the top five for 65.5% (CR5) and the top ten for 80.6% (CR10). After the tenth producer, additional producers contribute progressively smaller increments.

**Table 2.** Concentration, inequality and robustness summary for the Isla Arena attributable assemblage

| Metric | Value | Interpretation |
|---|---|---|
| Identifiable items (*N*) | 232 | Items assigned to a producer |
| Producers (*n*) | 48 | Distinct identifiable producers |
| Brands/products | 72/95 | Taxonomic resolution of the assemblage |
| Abundance Gini | 0.690 | High producer inequality |
| Abundance Gini, 95% CI | 0.629–0.698 | 10,000 item-level bootstrap replicates |
| Impact (CEI) Gini | 0.692 | Near-identical to abundance Gini |
| $\Delta G$ (Impact − Abundance) | 0.002 | Strong abundance–impact coupling |
| CR1 | 27.6% | Leading producer share |
| CR3 | 48.3% | Top three producers |
| CR5 | 65.5% (95% CI 59.9–71.6%) | Top five producers |
| CR10 | 80.6% | Top ten producers |
| Producers reaching 50% of load | 4 | 56 companies globally (Cowger et al., 2024) |
| IPW-corrected Gini | 0.714 | Corrected for category-specific attribution rates |
| Gini range, bounding scenarios | 0.220–0.898 | Full arithmetic bounds (Figure 8b) |
| Mean AHI | 0.754 | Average hazard score |
| Mean mobility | 0.594 | Average transportability score |

*Note*: Confidence intervals are percentile intervals from 10,000 item-level bootstrap replicates; the IPW-corrected coefficient re-weights each item by the inverse of the attribution probability of its item category.

films, low-grade paper labels or unbranded and informally produced items, which would push dispersed, small-scale contributors into the unattributed fraction and inflate the apparent concentration. Three analyses address this concern (Figure 8).

Sampling uncertainty is small: resampling the attributable items 10,000 times returned a bootstrap 95% confidence interval for the Gini coefficient of 0.629–0.698, and of 59.9–71.6% for CR5; the finite-sample corrected coefficient is 0.705. The point estimate lies near the upper limit of the percentile interval because the bootstrap distribution is left-skewed: each resample omits, on average, about a third of the 31 single-item producers and converts others into doubletons, reducing observed richness and flattening the tail, so replicate coefficients fall below the observed value far more often than above it (bootstrap median 0.667). The plug-in estimate is therefore, if anything, conservative, consistent with the finite-sample correction (0.705) moving it upward rather than downward. Rarefaction makes the same dependence explicit: sub-sampling the attributable pool to 50, 100 and 150 items reduced mean observed richness to 18, 28 and 36 producers and the mean coefficient to 0.48, 0.59 and 0.64, respectively. The Gini coefficient is thus invariant to the number of items for a given producer pool, but its expected value rises with detected richness and attribution effort, a dependence that the finite-sample correction does not remove.

Differential survival does not generate the result either. Attribution succeeded for 29.1% of rigid plastics, 88.9% of composites and 50.0% of aerosols and cans, but for none of the foams, glass bottles, caps or films. Re-weighting each attributed item by the inverse of the attribution probability of its own category corrects for exactly the mechanism of concern, and raises rather than lowers the coefficient to 0.714, with CR5 rising to 67.4%. The categories that lose traceability fastest are not those that would dilute producer dominance.

Bounding the unattributed fraction defines the limits of interpretation. If unattributed items are missing at random with respect

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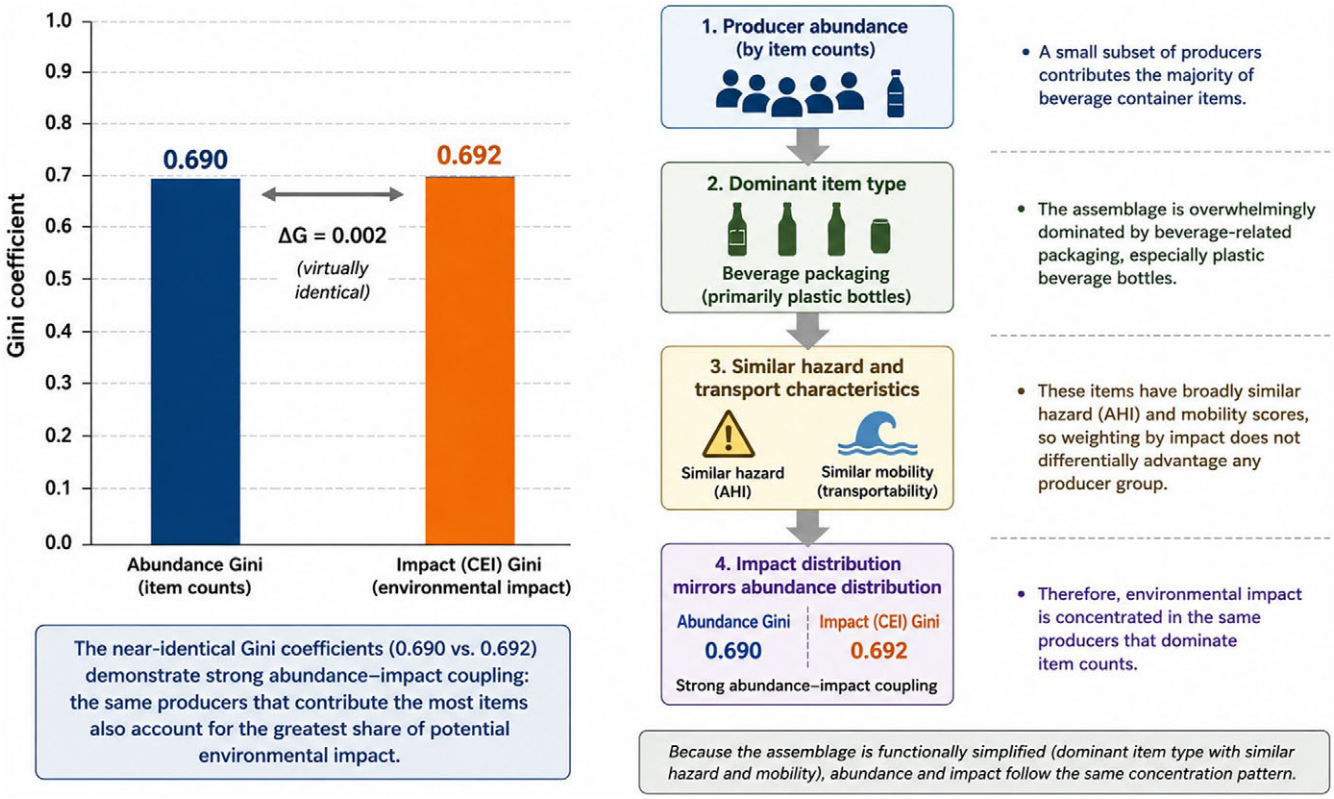



**Figure 7.** Abundance–impact coupling within the Isla Arena producer assemblage. (Left) Comparison between abundance-based and impact-based (CEI-weighted) Gini coefficients. The minimal difference between the two values (0.690 vs. 0.692; $\Delta G = 0.002$) demonstrates near-perfect correspondence between producer abundance and potential environmental impact. (Right) Conceptual model explaining the observed coupling. Because the assemblage is dominated by beverage-related packaging with similar hazard and mobility characteristics, environmental impact follows the same concentration pattern observed for producer abundance.

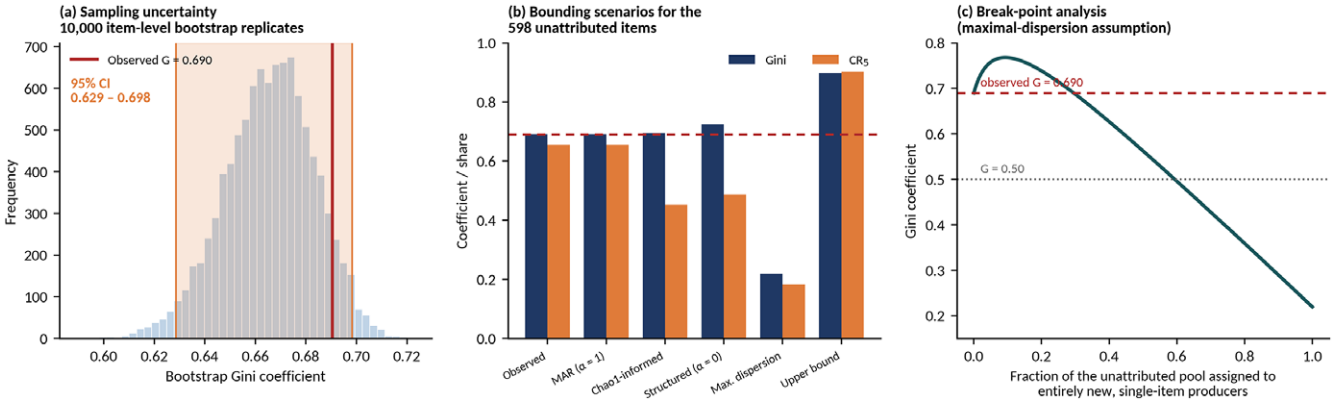



**Figure 8.** Robustness of the concentration estimate. (a) Distribution of the Gini coefficient across 10,000 item-level bootstrap replicates, with the observed value (0.690) and the percentile 95% confidence interval (0.629–0.698). (b) Gini coefficient and CR5 under bounding scenarios for the 598 unattributed items, from missing-at-random ($\alpha = 1$) through Chao1-informed and structured-dispersion allocations to the maximal-dispersion limit and the upper bound; the dashed line marks the observed coefficient. (c) Break-point analysis: the Gini coefficient as a function of the proportion of the unattributed pool assigned to entirely new, single-item producers. The coefficient remains above 0.50 unless more than 59% of that pool is assumed to originate from previously unseen producers contributing one item each.

to producers, every statistic is unchanged by construction. If they belong to previously unseen producers but reproduce the observed rank-abundance shape, the coefficient remains at or above the reported value (0.695–0.753). Only in the arithmetic limit in which each of the 598 unattributed items belongs to a different, otherwise absent producer does it fall to 0.220; that limit implies 646 producers, 5.5 times the richness of 117 estimated from the observed distribution by Chao1, and requires an assemblage in which no unbranded product is ever repeated. Between these extremes the coefficient remains above 0.50 unless more than 59% of the unattributed pool consists of entirely new single-item producers. Concentration ratios are more sensitive to these assumptions than the Gini coefficient and are therefore reported as conditional statistics of the attributable pool rather than as estimates for the

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total load – a distinction of limited practical consequence, since brand-based EPR instruments can only act on the traceable fraction in any case.

### Sources, transport and the meaning of concentration on a sink

The concentration patterns cannot reflect local disposal, since the island has no permanent population, infrastructure, commerce or resident waste generation; every item is imported. It is not a source but a receiving environment, so its assemblage is a regional rather than local signal.

Earlier work identified mainland recreation and waste disposal in adjacent drainage basins as the principal sources of the island's litter (Rangel-Buitrago et al., 2019, 2026). Isla Arena lies within the influence of the Magdalena River system, Colombia's largest basin, and smaller coastal watersheds (Pinzón et al., 1998) connecting urban, industrial, tourism and agricultural areas to the sea (Restrepo López et al., 2017). Longshore currents driven by north-east trade-wind swells move debris predominantly southwestward (Ortiz et al., 2025), forming a corridor along which litter generated tens to hundreds of kilometres away can reach the island, while extreme rainfall and flood-driven "litter blooms" deliver large pulses from river basins to the coast (Rangel-Buitrago et al., 2017, 2018). Its low elevation, overwash-prone morphology and small size then favour interception and retention, so that, unlike urban beaches where local disposal distorts transport signals (de Oliveira et al., 2025), the assemblage reflects the cumulative outcome of regional production, consumption, transport and retention.

In this light, the concentration revealed by the Lorenz curve and Gini coefficient gains broader meaning: the dominance of a few beverage producers is consistent with the structure of the regional production–consumption system rather than with the peculiarities of one island. This inference deserves an explicit caveat. The link between mainland sources and the island is established here from the regional circulation literature and from the origin declarations on the items themselves, not from a hydrodynamic model calibrated for this cay. Without particle-tracking or drift modelling the catchment actually sampled cannot be delimited, nor can the degree to which transport filters some packaging types more than others be quantified. The distribution measured here should therefore be read as the composition of what arrives at, and is retained by, one sink, and only provisionally as a proxy for the regional source system; coupling inequality metrics with Lagrangian transport modelling and replicating them across sinks with contrasting exposure is the natural next step.

Subject to that caveat, concentration translates into tractability: dispersed systems require engaging many marginal actors, whereas here a small subset accounts for most litter and most estimated impact, meaning fewer intervention points, fewer monitoring targets and greater efficiency for EPR measures (Pruess, 2023; Mallick et al., 2024).

### Implications for extended producer responsibility and governance

The concentration structure translates directly into management strategy (Figure 9). The assemblage shows high inequality, strong beverage-sector dominance and near-perfect abundance–impact coupling, indicating responsibility concentrated within a few actors and amenable to targeted intervention. The Gini coefficient thus diagnoses governance tractability, distinguishing high-Gini systems, where focused action on a few producers is possible, from low-Gini ones.

For Isla Arena the implications are clear: the five dominant beverage producers account for nearly two-thirds of attributable litter, so a few interventions aimed at them could influence much of the traceable stream. Deposit-return systems (Hartmann and Cavagnaro, 2025), mandatory recovery targets (Williams and Rangel-Buitrago, 2022), packaging redesign (Georgakoudis et al., 2018), reusable-container schemes (Kang and Park, 2026) and recycled-content obligations (Soomro et al., 2025) apply directly to these contributors, acting upstream where prevention opportunities are greatest (Williams and Rangel-Buitrago, 2019). Brand-level structure narrows the focus further: Pony Malta alone exceeds a quarter of attributable items. Standard frameworks flag beverage bottles as dominant but cannot say which producers or brands drive that category; combining THCPL attribution with inequality analysis turns monitoring from description into a prioritisation framework with specific targets.

The results also expose the limits of site-level cleanup. Because Isla Arena is a sink rather than a source, removal treats symptoms: while the upstream system is unchanged, new material keeps arriving by the same pathways. Cleanups bring local benefits but cannot alter the concentration structure generating the stream (Rangel-Buitrago, 2025b); effective mitigation requires action at the source (Tramoy et al., 2026).

Being invariant to the number of items, the Gini coefficient is also a monitoring tool, comparable over time and across locations regardless of litter abundance, provided that sites are compared at similar detectable producer richness or after richness standardisation (e.g., rarefaction to a common number of attributable items), and that each coefficient is reported with its n and any finite-sample correction applied. Repeated surveys could show whether responsibility grows more concentrated or diffuse after EPR, deposit-return or packaging measures, and comparisons among islands, beaches and estuaries could reveal how concentration varies across source-to-sink systems. The same logic applies to traceability itself: the share of items attributable at all is a measurable outcome of labelling and reporting policy, and a rising attributable fraction would be evidence that mandated producer reporting is working (Cowger et al., 2024). Identifying producers is informative, but quantifying how responsibility is distributed among them is operational, providing a rational basis for prioritising interventions.

### Strengths and limitations

The approach's principal strength is extracting a new, decision-relevant dimension from an existing dataset without extra fieldwork or monitoring. Whereas conventional assessments quantify abundance, composition and producer identity (Madricardo et al., 2020; Fleet et al., 2021; Schmid et al., 2021), the inequality framework quantifies how responsibility is distributed, and is transparent, invariant to the number of items, and ready for transfer across sites and periods once producer richness is standardised; the data and the complete analysis code are released with this paper so that every value can be recomputed and the framework applied elsewhere. A second strength is the site: uninhabited and free of local waste generation, Isla Arena's assemblage reflects imported litter, giving a clean view of a regional source-to-sink system.

Several limitations apply. First, the analysis rests on a single survey at one location, so the coefficient describes the assemblage at sampling time, not a stable condition; seasonal variability, storm transport, river-discharge changes and episodic litter blooms could shift composition over time, and repeated surveys are needed to test

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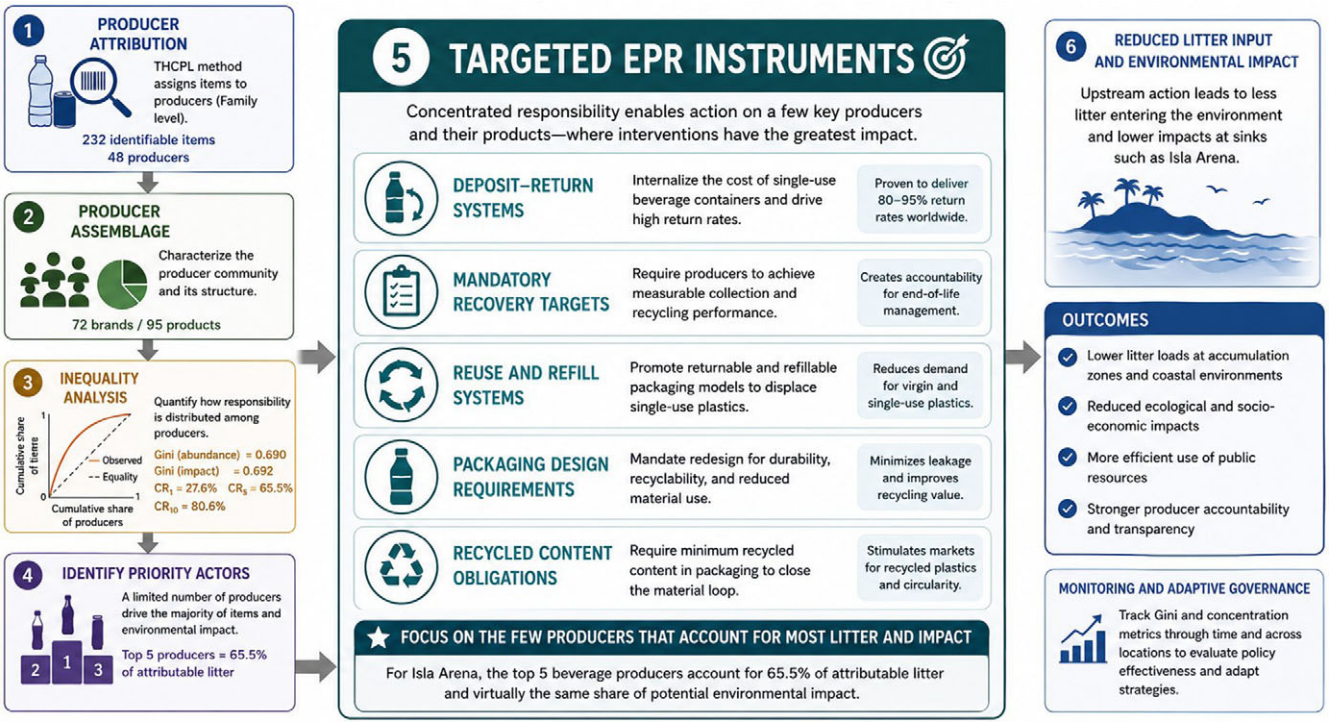



**Figure 9.** From producer attribution to governance: application of inequality analysis to targeted Extended Producer Responsibility (EPR). The framework illustrates the progression from producer attribution and assemblage characterisation to inequality analysis, identification of priority actors and selection of targeted EPR instruments. The concentration of responsibility among a small number of beverage producers enables focused interventions such as deposit-return systems, recovery targets, reusable packaging schemes, packaging redesign requirements and recycled-content obligations.

stability. Second, no hydrodynamic modelling was performed, so the source area feeding the island is inferred rather than delimited, and the regional interpretation of the producer distribution remains provisional pending drift or particle-tracking simulations. For the same reason, transferability is argued here rather than demonstrated: the pipeline has been applied to one assemblage, and its validation on independent producer-attribution datasets, including published brand-audit compilations such as Cowger et al. (2024), is the necessary next step.

Third, only 232 of 830 items (28.0%) retained enough information for attribution. The sensitivity analyses show that this does not overturn the result – bootstrap intervals are narrow, correcting for category-specific attribution rates increases rather than decreases the coefficient, and only an implausible maximal-dispersion limit reduces it – but they also show that concentration ratios computed for the traceable pool should not be read as shares of the total litter load. The rapid erosion of traceability is itself informative, and the conservative protocol favoured reliability over completeness.

A further limitation is aggregation: responsibility was evaluated at the producer (Family) level, combining products and brands under corporate structures, which suits governance analyses though other levels could yield different patterns. Likewise the CEI is a secondary layer built from item-type hazard and mobility scores rather than direct measurements of impact, and should be read as an approximation. Finally, the framework identifies where responsibility is concentrated within an observed assemblage; it does not measure production volumes, market shares or waste-management performance, and producers at the top of the distribution are often those whose products are most widely consumed, most frequently discarded, and most readily identifiable after environmental exposure.

Despite these limitations, the central finding is robust: the assemblage shows strong concentration whether measured by abundance or by potential impact, and under every correction and bounding scenario except the arithmetic extreme.

## Conclusions

This study shows that producer responsibility in a marine litter assemblage can be evaluated not only by presence but by distribution. Applying Lorenz curves and Gini coefficients to the attributable fraction of the Isla Arena assemblage, we find responsibility highly concentrated: of 48 producers identified, the five leading accounted for 65.5% of attributable litter, and the abundance-based Gini reached 0.690 (95% CI 0.629–0.698). Producer richness and influence are thus fundamentally different properties.

A second finding is the near-perfect correspondence between abundance and impact concentration: the two Gini coefficients differed by only 0.002 (0.690 vs. 0.692), so the producers contributing the most items also contribute the greatest potential impact. This coupling arises from the assemblage's functional simplification, dominated by beverage packaging, under which responsibility, abundance and impact converge on the same small group of actors.

The concentration is not an artefact of incomplete attribution: bootstrap resampling leaves it essentially unchanged, correcting for the differential survival of labels increases it to 0.714, and it falls only in an arithmetic limit inconsistent with the observed richness structure: that limit implies 646 producers against the 117 estimated

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by Chao1, and the coefficient remains above 0.50 unless more than 59% of the unattributed pool is assumed to come from entirely new single-item producers. What the analysis cannot do is extend concentration ratios from the traceable fraction to the total litter load, or delimit the source area feeding the island without hydrodynamic modelling.

From a governance perspective, the principal contribution is to show that inequality is a management-relevant property of marine litter systems: the Gini coefficient is both a descriptor and an indicator of governance tractability. For Isla Arena, concentration within a few beverage producers means EPR measures, deposit-return schemes, packaging redesign and recovery obligations can target a limited set of actors while addressing most of the attributable stream. More broadly, the Lorenz–Gini framework turns producer attribution into a quantitative instrument for environmental governance, ready for transfer to other producer-attribution datasets; its validation across multiple assemblages, compared at standardised producer richness, is the immediate next step.

**Open peer review.** To view the open peer review materials for this article, please visit http://doi.org/10.1017/plc.2026.10071.

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**Author contributions.** All authors contributed substantially to the conception and design of the study. Data acquisition, classification and analysis were performed collaboratively. The manuscript was drafted by the first author and critically revised by all co-authors for important intellectual content. All authors approved the final version of the manuscript and agree to be accountable for all aspects of the work.

**Competing interest.** The authors declare that there are no competing interests.

**Data availability statement.** All data and code needed to reproduce every result, table and figure in this article are openly available. The item-level macrolitter dataset (Supplementary Material S1), the analysis workbook (Supplementary Material S2) and the complete analysis script with its input weight table (Supplementary Material S3) are provided as supplementary files with this article. Running the script on Supplementary Material S1 reproduces all reported statistics, including the Lorenz coordinates, Gini coefficients, concentration ratios, CEI values, bootstrap intervals and sensitivity scenarios.

**Ethics and approvals.** Not applicable. This study did not involve human participants, animals or sensitive data.

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