Near or Far: Revealing the role of land-use on macrolitter distribution in Swiss freshwater

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Abstract. Rivers are generally considered as conduits for macrolitter into the sea. However, macrolitter and especially macroplastics can also negatively impact freshwater ecosystems, because items can be retained along lake shores, riverbanks, bed sediments or floodplains. Long-term and large-scale assessments of macrolitter on riverbanks and lake shores can provide an understanding of litter abundance, composition and origin in freshwater systems. Combined with information on hydrometeorological variables and characteristics of accumulation zones, potential leakage and transport processes can be further investigated. Several studies have already explored the role of hydrometeorological factors on macrolitter variability, but others, such as land-use characteristics have not yet been investigated. In this study, we provide a first assessment of land-use influence on macrolitter accumulation in freshwater systems. We analyzed the composition and origin of the most commonly found macrolitter items - "top items" - (n = 42,537) sampled across lake shores and riverbanks in Switzerland between April 2020 and May 2021. We explored the relationship between eight land-use variables (i.e. surface covered by built environment, recreational, industrial, agricultural areas, forests, unproductive land, road network length and number of rivers and canals present) and macrolitter abundance at survey locations (n = 143). We estimated that 45% of the top items (subset of all sampled items) are significantly and strongly correlated with the land-use characteristics of the survey location. This could indicate that these sites either have a high retention capacity or a high leakage rate of macrolitter. A bit over one-third of the items (34%) had no association with the local land-uses of the survey sites. Such items are likely to have been transported over longer distances before beaching, or do not preferentially accumulate at sites with certain land-uses.

Ultimately, this highlights the need to combine measures at the local and regional/national scales for effective litter reduction.

1 Introduction

Macrolitter is an ubiquitous environmental risk, affecting both aquatic and terrestrial ecosystems. A growing amount of observational evidence shows high levels of exposure of freshwater ecosystems to macrolitter, with plastic found as the dominant material (van Emmerik et al., 2020). Macroplastics can threaten ecosystems, injure animals, cause economic damage by clogging hydraulic infrastructures, and lead to increased urban flood risks (Azevedo-Santos et al., 2021b; van Emmerik and Schwarz, 2020). Despite these threats, the leakage processes and transport pathways of macrolitter in freshwater systems remain largely unknown. Large-scale quantification of macrolitter abundance in freshwater systems have only been undertaken since a few years (Barer and Kull, 2018; González-Fernández et al., 2021; Hengstmann and Fischer, 2020; van Emmerik and Schwarz, 2020). As a result, only few studies have so far explored the drivers of macrolitter variability in freshwater systems. Such studies would be crucial in informing litter reduction and mitigation strategies on the ground.

The most commonly used methods quantify macrolitter either at the water surface, or along the lake shores and riverbanks (Azevedo-Santos et al., 2021a; Castro-Jiménez et al., 2019; Mason et al., 2020; Tasseron et al., 2020; van Emmerik et al., 2019; van Emmerik and Schwarz, 2020). Floating macrolitter assessments typically use visual counting of macrolitter items from bridges or deploy nets to retrieve water samples from boats or bridges. These monitoring techniques require the presence of infrastructure and/or the availability of equipment. In addition, they only provide a 'snapshot' view of the quantity and composition of floating litter at a given time. By contrast, monitoring macrolitter accumulations on river and lake banks allows to cover larger geographical areas and to conduct more frequent observations (Vriend et al., 2020). As a result, some countries have deployed large-scale monitoring programs of macrolitter abundance along riverbanks and lake shores, often relying on the participation of trained volunteers. This is the case in the Netherlands with the *Schone Rivieren* (Clean Rivers) initiative, the Swiss Litter Report in Switzerland and the Great Canadian Shoreline Cleanup (Barer and Kull, 2018; Hengstmann and Fischer, 2020; van Emmerik and Schwarz, 2020). These large-scale and long-term monitoring programmes provide baseline estimates of macrolitter quantities and composition. They can also be used to explore fundamental transport and accumulation processes of macrolitter in freshwater systems.

Despite baseline assessments of macrolitter in freshwater ecosystems becoming more common, the factors determining its variability remain to date largely unresolved. Macrolitter found on riverbanks and lake shores comes either from terrestrial pathways (by direct littering or dumping) or from transport from the aquatic systems (by river flow and lake surface current). It is commonly assumed that hydrometeorological variables, such as precipitation, wind speed, water flow velocity and river discharge play an important role in the transport and deposition of macrolitter items along the banks of freshwater bodies (Bruge et al., 2018; Haberstroh et al., 2021; Liro et al., 2020; Roebroek et al., 2021). Other factors affecting macrolitter transport and accumulation processes pertain to the items characteristics (e.g. buoyancy, level of biofouling) and the aquatic system characteristics (e.g. meanders and channel width in the case of rivers) (Lechthaler et al., 2020; Lobelle et al., 2021; Newbound, 2021). Macrolitter abundance on riverbanks and lake shores can also come from mobilisation through terrestrial pathways (Mellink et al., 2022). In this case, wind speed and surface runoff are also presumed to be major drivers of macrolitter transport (Lebreton et al., 2017; Meijer et al., 2021; Roebroek et al., 2021). A study on macrolitter abundance on the Dutch riverbanks demonstrated the influence of hydrometeorological factors, but also highlighted that the studied variables (wind speed, flow velocity and precipitation) only accounted for 19% of macrolitter variability (Roebroek et al., 2021). Other potential driving factors have not yet been studied in relation to macrolitter abundance and composition in freshwater systems but may play an important role. These include stochastic events such as direct littering and dumping of macrolitter close to freshwater systems. One of the crucial open questions remains the role of local leakage processes in macrolitter presence along lake shores and riverbanks. Investigating the impact of differing land-uses on macrolitter quantities, in relation to items origin and composition can ultimately improve our understanding of leakage and (terrestrial and aquatic) transport mechanisms of macrolitter into freshwater systems. Ultimately, this could enable to distinguish different leakage and transport mechanisms based on their relevant geographic scale. As such, this investigation could provide a first step to differentiate between locally and non-locally leaked items, as well as items transported for short distances and items travelling long distances before beaching.

Land-uses are an explaining factor for variability in macrolitter accumulation in coastal, marine and land environments (Aydin et al., 2016; Grelaud and Ziveri, 2021; Harris et al., 2021; Pietz et al., 2021), but no such studies have been conducted for freshwater systems. The proximity of land-based litter sources, such as recreational and urban areas might be an indicator for high leakage rates (i.e.: high littering rates and losses into the environment). Impervious surfaces also generate higher surface runoff volumes, which in turn can accelerate leakage and propagation of litter from land to the aquatic environment (Baldwin et al., 2016). Many regional and global scale studies model plastic waste inputs into lakes, rivers and oceans as a function of nearshore population densities, generally using global population datasets (Hoffman and Hittinger, 2017; Jambeck et al., 2015; Lebreton et al., 2017; Schmidt et al., 2017). However, higher human densities do not necessarily translate in higher rates of leakage into the environment at a local scale (Schuyler et al., 2021). This highlights that population density should not be used as the sole proxy for litter inputs for accurate modelling of its distribution in the environment. Land-uses may play an important role in macrolitter accumulation, as they can highlight specific point sources of macrolitter items (e.g.: industries, commercial areas) or degree of frequentation of places (e.g.: recreational areas) that could lead to higher leakage rates into the environment. The role of several land-use variables should be considered but has so far not been thoroughly quantified in relation to empirical data on macrolitter abundance. Such insights are relevant for several reasons. First, a better understanding the leakages and transport processes of litter pollution is crucial in designing targeted intervention strategies and formulating policies to prevent and reduce their leakage into the environment. Second, they can be used for improving large-scale models on debris distribution and propagation into the environment.

In this study, we elaborate on the hypothesis that land-use features (partially) explain the variability in macrolitter abundance and composition in freshwater systems. We used an extensive observational dataset on macrolitter abundance, collected across Switzerland in 11 lakes and 17 rivers. 385 surveys were conducted over a 13-month period, during which 50,469 macrolitter items were sampled on Swiss riverbanks and lake shores. We analyzed the composition and likely origin of the most commonly found macrolitter items (n = 42,537) - hereby referred to as 'top macrolitter items'. We then assessed the role of dominant land-use variables (i.e. surface covered by built environment, recreational, industrial, agricultural areas, forests, unproductive land, road network length and number of rivers and canals present) on macrolitter abundance among top items. Based on this analysis, we provide an initial categorization of item leakage processes into the environment, and distinguish items which presence can be attributed to local land-use characteristics and items likely to have been transported over longer distances.

2 Data and Methods

For all the survey locations (n = 143) we conducted a statistical analysis that coupled macrolitter abundance and composition and the land-use characteristics of each location.

Macrolitter dataset

The macrolitter data used in this research was collected between 1 April 2020 and 31 May 2021 by the NGO Hammerdirt, in a project sponsored by the Swiss Federal Office for the Environment. Overall, 385 surveys were conducted at 143 locations, in 77 different municipalities in Switzerland. In total 50,469 macrolitter items were counted and categorized using the Marine Litter Beach item classification method (see Fig. A1). Of the 385 surveys, 331 (86%) were undertaken on lake shores and the remaining 54 (14%) on riverbanks. The surveys were conducted by Hammerdirt staff and trained volunteers. Several criteria determined the selection of the survey locations. Firstly, the survey area must be a bank of a lake or river, with direct contact with the water. Small ponds and streams were excluded, and the survey locations typically comprised between 50 and 200 m^2. Secondly, survey locations were required to be accessible (both physically and legally) throughout the year. Also, the site must be within 30 minutes of the nearest public transport station to ensure that surveyors could easily reach it. Finally, survey locations that had already been selected for the Swiss Litter Report (Barer and Kull, 2018) in 2018 were preferred over new survey locations to facilitate future time-series analysis. In addition to the macrolitter sampling, the surveyors also measured the length and width of each survey location. The length of the sampling area was determined as the longest continuous stretch of lake shore or riverbank accessible. Despite international protocols such as OSPAR requiring to survey beaches of 100 m of length (OSPAR Commission, 2010), this was not possible in the Swiss context, given that the majority of beaches have smaller strips of land available (due to both legal and physical barriers), with a site median length for the surveys considered in this study of 45 m. The width of the survey area was defined as the distance from the waterline to the high-water line.

During each survey, participants collected all visible items >5 mm in size (i.e. macrolitter). Items were subsequently categorized using the Marine Litter Beach item classification, which contains a total of 217 categories (on Marine Litter, 2013). All items collected and analyzed during each survey were then categorized by material types (plastic, glass, metal, cloth and paper). We also indicated for each item category their likely type, namely: plastic fragments and pieces, industry, tobacco, food and drinks, sanitary, non-food packaging and others. This classification by items type was done by using the description of each macrolitter category as an indicator for the type and origin of items. Items for which no clear type could be inferred from the category description were categorized as 'Others'. Table 1 details all the item categories per item type. Macrolitter abundance was ultimately reported in both total items count and number of items/100 m of shoreline, in line with the EU Marine Litter Baselines, which express marine macrolitter abundance in items/100 m of shoreline (on Marine Litter, 2013).

Land-use datasets

We extracted land-use characteristics for each survey location. This involved defining a buffer area with a radius of 1,500 m around each survey location and extracting the percentage of land-use categories at each area, as well as the total road network length and the number of rivers and canals intersecting this area (Fig.1). Initially, several buffer area radii were tested for the analysis, ranging from 1,500 to 10,000 m. Ultimately, the buffer area of 1,500 m was retained for extracting land-use features (see Appendix B for the justification on the choice of the buffer area size).

We used the Swiss Land Use statistics to extract land-use categories at each survey location. This dataset is freely available and is updated every year (Confédération suisse, 2021). The dataset has a resolution of 100 m x 100 m and covers the entire country. At each grid point, one land-use category is assigned out of 46 total categories, following the 2004 standard classification of the Swiss Federal Statistical Office (BFS, 2017). The 46 categories were aggregated for this study into 8 main parent-classes: 1) Built environment (classes 103-108) 2) Industries (classes 101-102) 3) Transport surfaces (classes 121-125 and 141-147) 4) Agricultural areas (classes 201-203 and 221-223 and 241-243) 5) Forests and woods (classes 302-304) 6) Lakes and rivers (classes 401-403) 7) Unproductive land (classes 421-424) 8) Recreational area (classes 161-166). Appedix X details the 46 categories and their parent-classes. Recreational areas include diverse public uses, from sport fields to cemeteries and captures all land surfaces dedicated to social activities. Ultimately, only five of these parent-classes were considered for analysis in relation to macrolitter abundance: built environment, industrial areas, recreational areas, agricultural areas and forests. The transport surface, as well as the area covered by lakes and rivers was not included, as it is redundant with variables extracted from another dataset (see next paragraph), which offers a higher spatial resolution. The land-use profile was expressed in percentage (%) of the total terrestrial surface of the 1,500 m buffer zone around the sampling site, for each land-use category considered. To determine the total terrestrial surface, lake and river surfaces were subtracted from the total surface.

All streets and pathways from the swissTlmRegio dataset were combined and intersected within the 1,500 m buffer area defined around each sampling location. The total road network length was then calculated and expressed in kilometers (km). Similarly, the number of rivers and canals intersecting was counted within the 1,500 m area of each survey location, also using the swissTlmRegio data. The extraction of land-use variables was done using QGIS (QGIS Development Team, 2021).

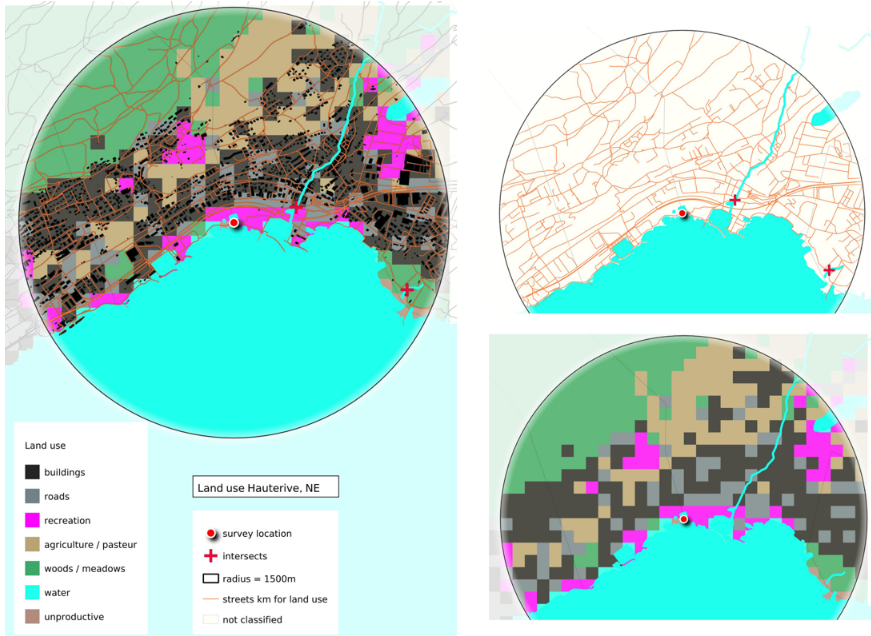

Figure 1. Example for extracting land-use profile, road network length and counting the number of intersecting rivers at one survey location. The example is from the Hauterive survey location (47.009296, 6.976259) at the Neuchâtel lake, Switzerland

The dominant land-use class is forests (median value of 25.5%), followed by agricultural areas (24.9%) and built-up environment (23.5%). Recreational areas, industrial areas and unproductive land represent lower shares of the land-use (respectively: 3.5%, 2.0% and 0.7%). The median length of the road network is of approximately 67 km and a median value of 3.0 was found for the number of rivers and canals intersecting the buffer area (Fig.2).

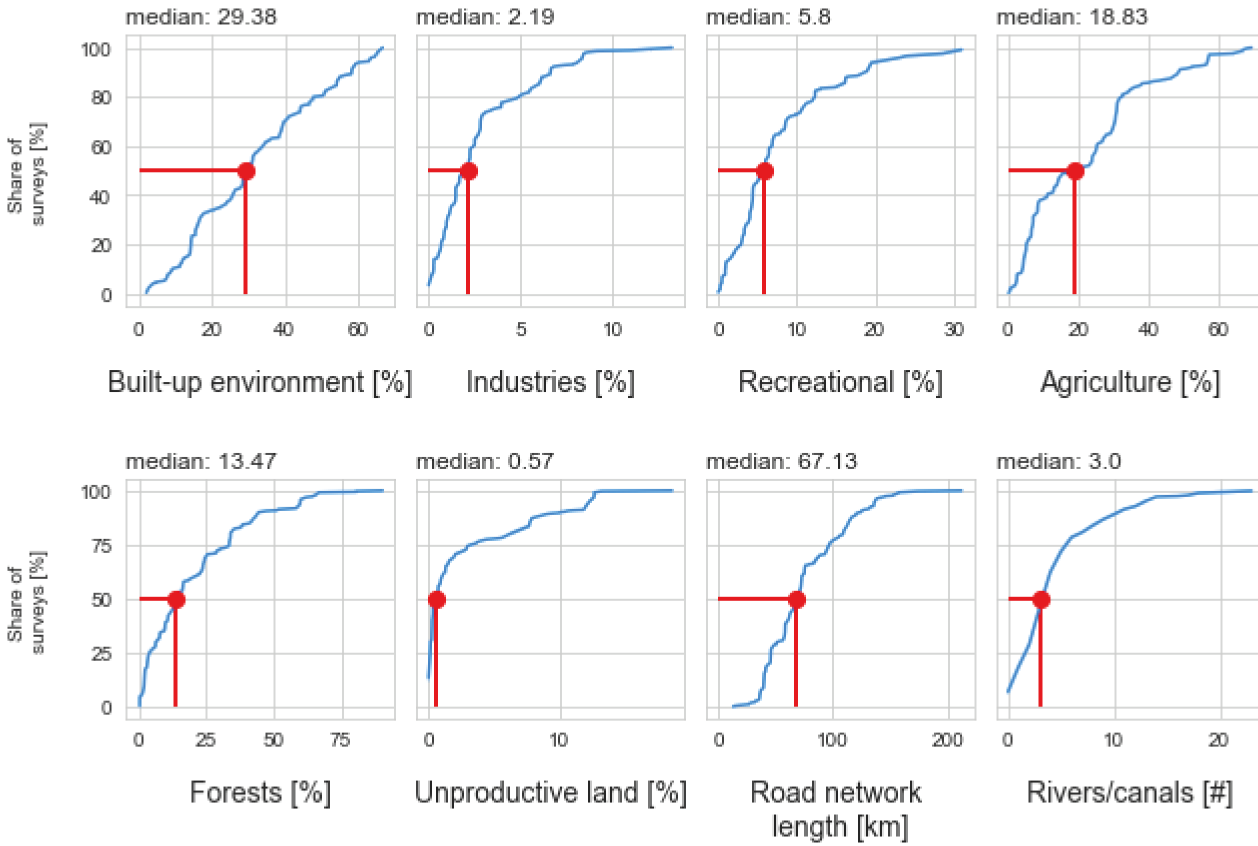

Figure 2. Land-use characteristics for the survey locations in Switzerland (n = 143), for a buffer area of 1,500 m. The red lines and point show the median values for each land-use feature.

Data analysis

We identified macrolitter items commonly found during the sampling at the national scale. Items found at least 20 times during one sampling were considered as commonly found. For each of these most found items, the abundance (expressed in items/100 m) was then correlated with several land-use variables. We calculated the correlation between the land-use variables and top macrolitter items at each sampling location. The correlation analysis used the Spearman correlation coefficient, which enables to test the statistically significant monotonic relationship between two variables (Mathematics Education Innovation). The null hypothesis is that there is no correlation between the land-use variables and the top items. The test results relate the direction (R) of a correlation and whether that association is likely due to chance (p-value). For a correlation to be considered significant, the p-values need to be inferior to 0.05.

3 Results and Discussion

Top items: main characteristics

A total of 50,469 macrolitter items were sampled in Switzerland between 1 April 2020 and 31 May 2021. These items belonged to 211 different categories, reflecting the various sources and types of items found. We identified 36 categories of items for which a minimum of 20 items were counted during at least one survey. These top items represent 84.3% (n = 42,537) of the total items found. The most abundant items were mainly identified as plastic material (89.4%) while other materials include glass (6.3%), metal (2.9%) and paper (1.1%). Among top items, the categories featuring in the top 20 (fig.3) include cigarette filters, fragmented plastics, expanded polystyrene and food wrappers. Fragmented plastics include all plastic types (e.g.: foil, hard and foam fragments). Table S1 in Appendix C presents a complete overview of top items abundance (both absolute and relative), their type and dominant material.

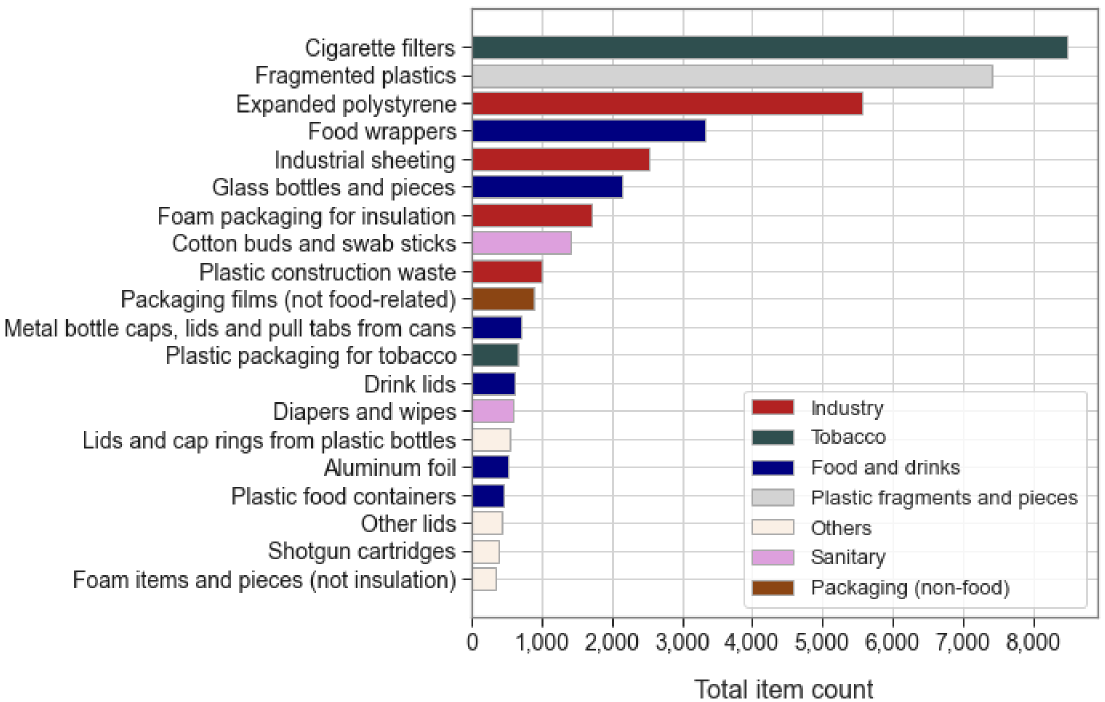

Figure 3. Top 20 macrolitter items found in Switzerland (n = 39,656 - 78.6% of total items sampled) and their likely origin.

Interestingly, a considerable amount of items can be attributed to the industrial and construction sectors, despite industrial areas not representing a large share of land-use (median of 2.0% across all surveys). Expanded polystyrene is often used as insulation material in the construction sector, and industrial sheeting is commonly used in the horticulture, industrial and construction sectors. Overall, items from the industrial sector represent a total of 11,341 items, making up for the largest type of items found: 22.5% of the total items and 26.7 % of top objects (Table 1). These items are not associated with consumer littering behavior. One hypothesis is that these items are leaked into the environment by accident, either close to their manufacturing sites or while being transported. On the contrary, the presence of food and drinks related objects, as well as tobacco products (respectively 18.1 and 20.5 % of top items), can be attributed to direct littering behaviors from consumers. Food wrappings and packaging, cigarette filters and glass bottles are likely to be directly littered from land by visitors. Whether the littering happens exactly on the sampling site or whether the items are transported (either from land or through the aquatic system) from nearby frequented places is unknown. Some sanitary products likely make their way into the environment from wastewater treatment plants (WWTPs). Cotton buds and swabs, sanitary pads and tampons may not get retained by WWTPs due to their (relative) small size. Mapping the locations of WWTPs and beaches where these items are frequently found might be useful in establishing whether WWPTs are a potential source of sanitary products into the environment. Because of their reduced size and fragmented state, identifying a clear pathway for plastic fragments and pieces is more difficult. Fragmentation and degradation could be the result of long stays in the water, or the weathering of larger plastic items present on beaches. Fragmented items were found in high proportions (16.6% among top items), thus requiring further investigation of their transport pathways and sources.

Except from the higher share in items attributed to the industrial sector, the composition of the top macrolitter items found in Switzerland is similar to that found in other observational studies on macrolitter abundance across Europe. Tramoy et al. (2019) found that plastic pellets, unindentified fragments and sticks (cotton buds and lollipop sticks) were the most abundant objects accumulated on the riverbanks of the Seine river, France. Other abundant items included expanded polystyrene, caps and industrial packaging films (Tramoy et al., 2019). Plastic fragments, food wrapping and packaging, caps and lids, cotton swabs and cigarette filters also feature among the top 20 items found on Dutch riverbanks (van Emmerik and Schwarz, 2020). These items were also among the top 10 litter items collected on the riverbanks of the Adour river in France (Bruge et al., 2018). This consistency in macrolitter composition is likely the result of similar consumption patterns and waste management practices among European countries. Another explaining factor might be that transport and deposition affect specific litter items differently and that thus, the items commonly found on freshwater shores are those preferentially deposited, due to their characteristics and transport processes. Among the top macrolitter items found in the above-mentioned studies and in Switzerland, several categories indicates high amounts of caps and lids. In contrast, plastic bottles were seldomly found. This probably indicates that the plastic bottles sink, whereas the caps stay afloat and wash up on the shores due to the combined action of wind, current and discharge, as suggested by Bruge et al. (2018).

Table 1. Top items characteristics (origin, item count, proportion and categories). The proportion, expressed in percentage, indicates the ratio of each type of items over the total count of top items

Type	Item count	Proportion [%]	Proportion plastic items [%]	Item categories
Industry	11,341	26.7	96.9	Expanded polystyrene; Industrial sheeting; Pellets; Foam packaging for insulation; Plastic construction waste; Ceramic tile and pieces; Plastic sheeting for large cargo items; Construction materials (bricks, pipes, cement); Pellet mass
Tobacco	9,134	21.5	100.0	Cigarette filters; Plastic packaging for tobacco
Food and drinks	8,038	18.9	58.2	Food wrappers; Glass bottles and pieces; Metal bottle caps; lids and pull tabs from cans; Drink lids; Aluminum foil; Plastic food containers; Plastic bags and pieces
Plastic fragments and pieces	7,400	17.4	100.0	Fragmented plastics
Others	3,159	7.4	86.8	Lids and cap rings from plastic bottles; Others lids; Shotgun cartridges; Foam items and pieces (not insulation); Fireworks (rocket caps, exploded parts and packaging); Lids for chemicals and detergents; Labels and bar codes; Foamed EVA; Glass and ceramic fragments (>2.5 cm); Fireworks (paper parts); Clothing and rags; Ribbons and bows
Sanitary	2,450	5.8	90.2	Sanitary pads, tampons and applicators; Diapers and wipes; Tissues, toilet paper and paper towels; Cotton buds and swab sticks
Packaging (non-food)	1,015	2.4	88.1	Paper packaging, Packaging films (not food-related)

Land-use influence

To assess the influence of land-use on macrolitter abundance and composition, the correlation was calculated for pairs of land-use variable and items, for top item categories. Figure 4 details the Spearman correlation coefficient (R) found for each combination. Among land-use variables, the number of rivers and canals intersecting the buffer area resulted in the highest number of associations (17, all positive). Agricultural land had in total a higher count of associations with litter abundance (19 significant correlations), but all were negative, thus indicating that agricultural land-use typically does not signal litter accumulation zones. The share of buildings, recreational areas and the length of the road network also seem to be good explaining factors for litter abundance, with positive significantly correlations found for 12, 11 and 11 item categories respectively.

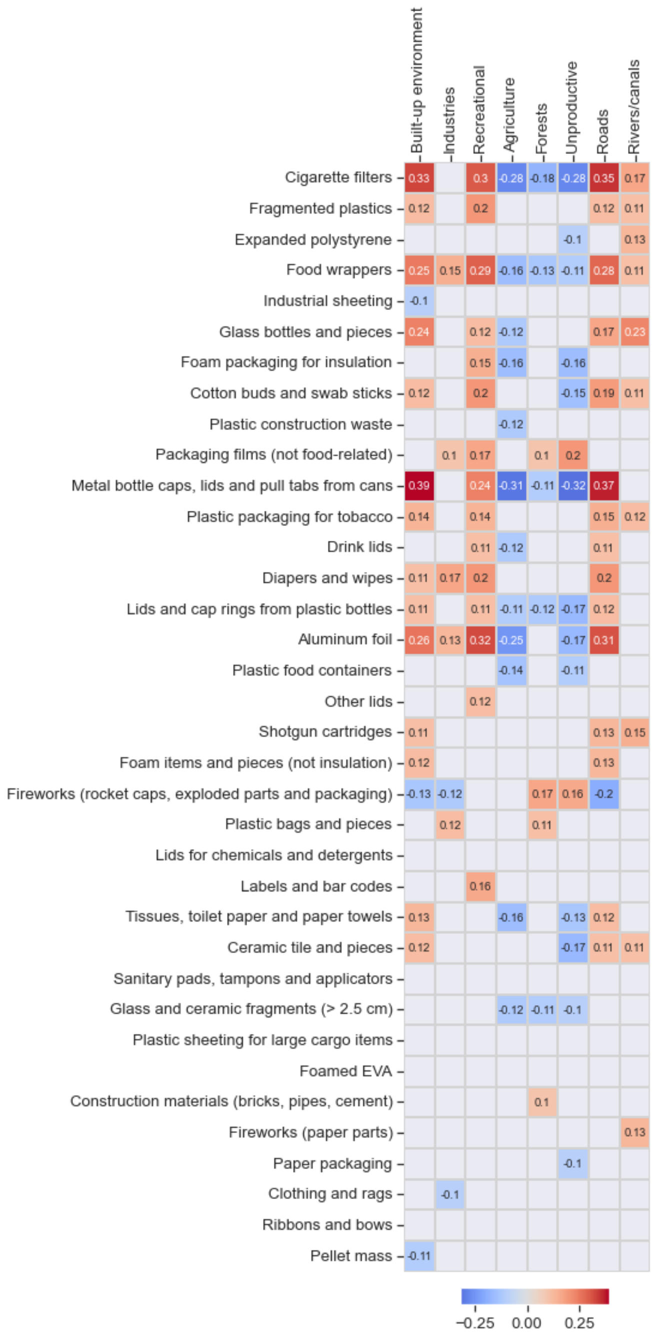

Figure 4. Correlation matrix for the most commonly found items on lake shores and riverbanks in Switzerland. Each square details the Spearman correlation coefficient (R) for p-values below 0.05 for each item category and land-use variable combination. For combinations where the p-value is below 0.05, no R value is indicated, as the relationship is considered non-significant. Item categories are listed in the order item count, from the most abundant category to the least commonly found.

In comparison, fewer categories were found to be positively associated with the presence of industrial buildings, unproductive land and forests (respectively 7, 4 and 2). This is not completely surprising given the lowest share of land-use these categories represent.

The correlation analysis for specific item categories illustrates that the explanatory power of land-use features strongly depends on item characteristics, their origins and associated pathways into the environment. Categories of macrolitter items can be classified into three groups that differentiate items based on the type (positive or negative), number and nature of associations with land-use features. We aim at providing a first level of identification of leakage processes and sources of entry of items. It should be noted that we considered the number of waterways intersecting the buffer area as a separate variable. Indeed, this variable likely indicates potential trajectory of items outside of the 3,500 m area, whereas the other land-use variables identify local characteristics.

1) Items that have several (more than or equal to 3) positive associations with land-use features, with the exception of the number of waterways intersecting the buffer area. The accumulation of these items on riverbanks and lake shores is likely due to local stochastic events (i.e.: local dumping and littering behaviours). Items in this group can be assumed to have their **primary source within the 3,500 m buffer area**, and have been transported through short-distances before beaching. A total of 9 categories are found in this group, amounting to 19,464 items (43.7% of top items). Item categories here include: cigarette filters, food wrappers, glass bottles and pieces, pellets, cotton buds and swab sticks, diapers and wipes, metal bottle caps and lids and aluminium foil and foam items and pieces (not insulation).

2) Items that have few positive associations (1 or 2) with all land-use features (except number of waterways intersecting) and that are also positively correlated with the number of waterways intersecting the buffer area. Items likely have probably been leaked outside of the 3,500 m buffer area. These items are likely to be deposited on freshwater shores as the result of **longer-distance transport processes through rivers upstream of their accumulation site**. We counted 11 categories of top macrolitter items in this group, for a total of 18,465 (41.5% of top items). The categories found in this group are: fragmented plastics, expanded polystyrene, foam packaging for insulation, plastic construction waste, plastic packaging for tobacco, lids and caps rings from plastic bottles, plastic food containers, other lids, shotgun cartridges, ceramic tiles and pieces and construction materials (bricks, pipes and cement).

3) All other items. These correspond to items with no or few significant correlations (less than 2) found with land-use features and no positive association with the number of waterways intersecting the buffer area. We found 18 categories of top items in this group, for a total of 6,576 items (14.8%). Items in this group are predominantly the **least abundant items found**, with 14 item categories counting less than 300 items. Categories here include: plastic bags and pieces, lids for chemicals and detergents and foamed EVA. Some more abundant items can be found as well in this group, such as industrial sheeting (n = 2,534). For this group, the leakage processes of macrolitter items cannot be determined. One reason for this might be that many items within this group are fragmented and therefore their categories are less homogeneous and indicative of their uses. As a result, items that can originate from different sources (households, industry, packaging) can be mixed in some of these item categories.

This categorization of macrolitter items based on their associations with land-use features bears many uncertainties. One bias stems from the assumption that all items belonging to a category are leaked and transported into the environment in the same manner. For non-identifiable items (i.e. fragmented items and pieces), the origin and thus pathways is even less likely to be homogeneous within a category. Furthermore, the few associations found for the third group of items could be the direct consequence of the lower count of items, as it may not enable reliable statistical analysis. Due to these biases, the categorization presented above should be taken as a first (tentative) effort to differentiate leakage processes and transport pathways of macrolitter items in freshwater systems. As such, it may need to be adjusted by using finer resolution land-use datasets (see section 4) and expanding it by incorporating other observational datasets. Despite its limits, this categorization ultimately highlights that many items are leaked close to their accumulation sites and that their presence at surveying sites can be attributed to local land-use features. This is in good agreement with recent findings that showed that items typically travel short distances between their leakage source and beached site (Newbound, 2021; Tramoy et al., 2020; Weideman et al., 2020). A similarly large portion of items, however, is most likely leaked outside of this area and transported from upstream through waterways.

4 Synthesis and outlook

The results of this study can be used to explore at which geographic scale litter mitigation and prevention programs are more suitable for effective reduction of specific items in freshwater systems. Local mitigation projects would be most beneficial to reduce the amount of items for which land-use was a good explaining factor of abundance - e.g. cigarette filters, food wrappers and metal bottle caps and lids, aluminum foil. On the contrary, for macrolitter items that have few or no association with land-use features, large local (municipal) investments are unlikely to be impactful in reducing their amounts in the environment. For these items, such as expanded polystyrene, plastic construction waste, foam packaging for insulation, reduction strategies at a regional scale would likely be more effective. Many of these items with few or no positive associations with land-use features come from the industrial and construction sectors. Therefore, associating this sector would therefore be needed for designing mitigation strategies to prevent the spilling of industry-related items into the aquatic environment. Ultimately, regional and local mitigation strategies need to be combined for impactful litter reduction, given the high proportions of both macrolitter objects associated to land-use characteristics and items non-locally leaked.

In this study, we analyzed the role of eight land-use features in explaining macrolitter variability. The role of several land-use features was not included in this study, although they might explain macrolitter abundance and composition. For instance, georeferenced data on wastewater treatment plants (WWPs) would also enable to explore the role of this infrastructure in macrolitter abundance. To the best of our knowledge, such datasets are currently not openly available for the entire Swiss territory. In addition, the land-use dataset used to extract 6 of the 8 land-use variables (i.e.: buildings, industrial, recreational, agricultural areas, unproductive land and forests) has a relatively coarse spatial resolution (i.e.: 100 x 100 m). Consequently, small areas and buildings dedicated to certain land-uses might not be captured in this land-use classification. For example, several small and medium size industries and manufacturer sites are likely to be missed. The correlation analysis showed a low number of positive associations with industrial areas, which may be a direct result from the land-use dataset coarse spatial resolution. Because of this limitation, we recommend exploring the association between macrolitter abundance and land-uses with higher resolution datasets. Such geographic database might be collected in a vector format, through crowd-sourced web applications such as Open Street Map (OSM). The high coverage at the global level - variable though depending on the regions - and the overall good quality of this openly licensed source of geospatial data make it a good fit for further studies on land-use influence on macrolitter composition. Barrington-Leigh and Millard-Ball (2017) found that as much as 80% of the world's roads had been mapped by OSM(Barrington-Leigh and Millard-Ball, 2017). The identification of industrial areas by OSM was estimated to be 83.0 % accurate for China (Zhou et al., 2022). Using global and openly available datasets on land-use features might also permit to extend the scope of such analysis to other regions in the world.

5 Conclusion

This study was the first to investigate the role of land-use features on macrolitter abundance in freshwater ecosystems. We highlight two clear differential leakage processes, pathways and sources for the top items found. Approximately 44% of top items are likely to have been leaked close (within a 3,500 m radius) to their beaching site. Another large portion of items (close to 42% among top items) have been leaked further away (outside of the 3,500 m buffer area). Among the latter group, items from the industrial sector were particularly abundant. Ultimately, these findings indicate that targeted solutions for litter reduction strategies need to be defined at different geographical scales for effective impact. Further, given that abundance of a large portion of items could not be explained by local land-use characteristics, waste emission models into the sea should critically reconsider the sole use of population datasets as proxies for leakage rates into the environment. Both for designing litter reduction strategies and the understanding of litter propagation from land to sea, differentiating items based on their origins, leakage processes and sources is therefore crucial.

Appendix A: Survey locations in Switzerland

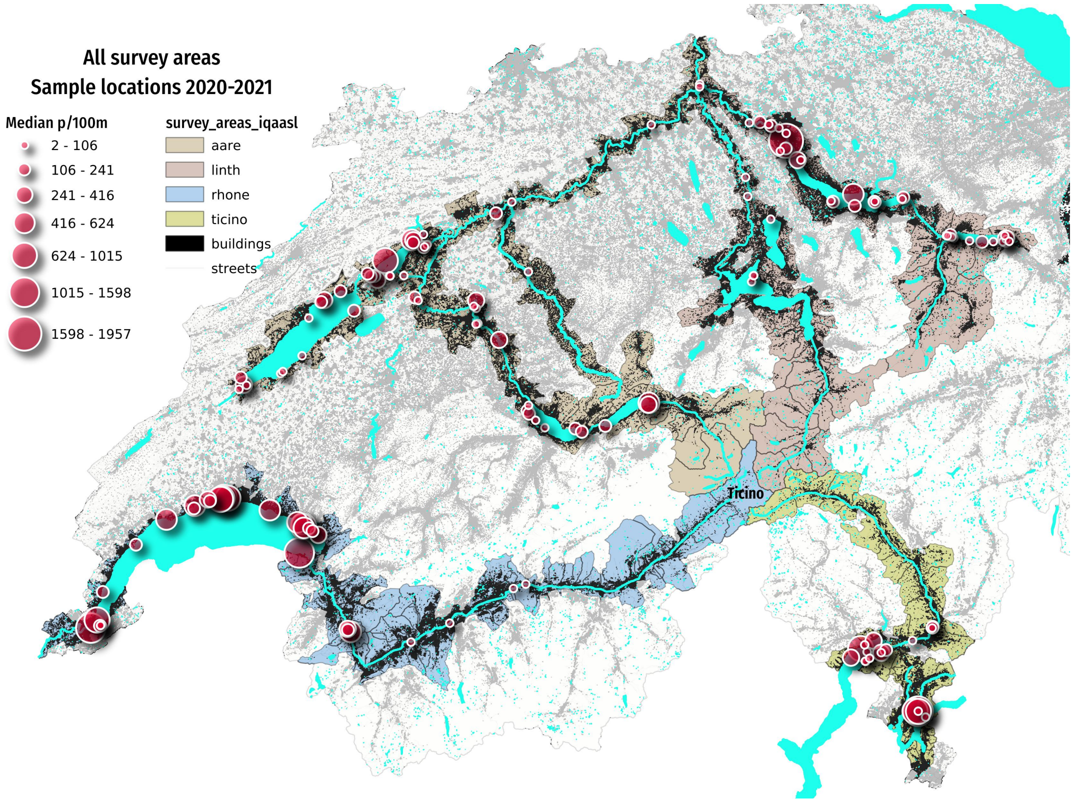

Figure A1. Map of survey locations for macrolitter sampling across Switzerland. The size of the marker is set by the median items count/100 m for that location.

Appendix B: Selection of buffer area radius

Nine different radii were tested for the correlation analysis between pairs of macrolitter items and land-use features: 1,500; 2,000; 2,500; 3,000; 3,500; 4,000; 4,500; 5,000 and 10,000 meters. Given that our study focuses on assessing the potential role of different land-uses in macrolitter abundance and composition, we first selected the buffer areas that yielded the highest number of significant correlations. This was the case for buffers of 3,500 m and 5,000 m of radius, which both had a total of 107 combinations. Among these two, we ultimately selected the buffer of 3,500 m because it resulted in a higher proportion of positive significant correlations compared to the 5,000 m buffer. The main differences in the correlation analysis among different buffer areas can be explained by the change in land-use profiles. The larger the buffer area, the highest the share of land-use features associated to rural environments (i.e. forests, unproductive land, agricultural areas). Smaller buffer areas, on the contrary, showed a more urban profile, with higher portions of land dedicated to buildings, industries, recreational areas and transport surfaces (Fig. A1).

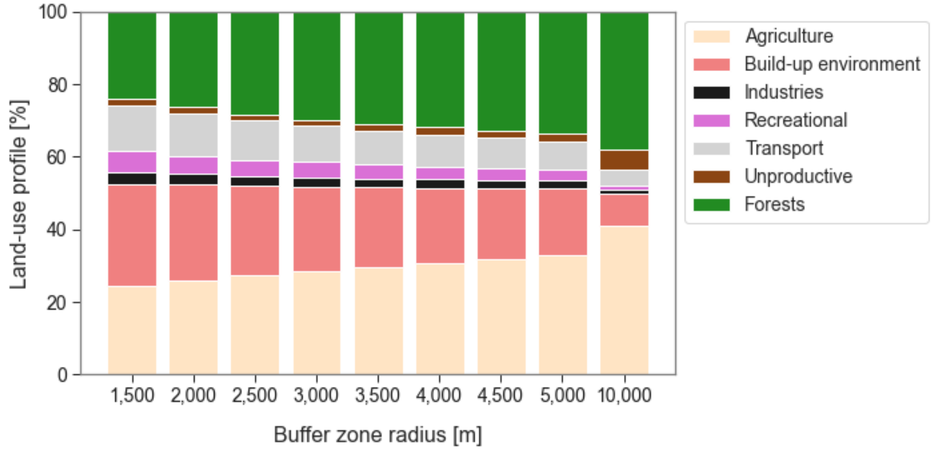

Figure B1. Land-use profile for different buffer zones. This figure only represents certain land-use features considered in the analysis, the road network length and the number of rivers/canals intersecting the area are not represented here given that they are not expressed in percentage.

Appendix C: Table S1

Description	Items count	Proportion [%]	Frequency [# items/100 m]	Type	Main material
Cigarette filters	8,485	16.8	54.3	Tobacco	Plastic
Fragmented plastics	7,400	14.7	59.2	Plastic fragments and pieces	Plastic
Expanded polystyrene	5,563	11.0	43.5	Industry	Plastic
Food wrappers	3,325	6.6	23.6	Food and drinks	Plastic
Industrial sheeting	2,534	5.0	18.9	Industry	Plastic
Glass bottles and pieces	2,136	4.2	16.2	Food and drinks	Glass
Foam packaging for insulation	1,702	3.4	13.1	Industry	Plastic
Cotton buds and swab sticks	1,406	2.8	10.7	Sanitary	Plastic
Plastic construction waste	992	2.0	7.1	Industry	Plastic
Packaging films (not food-related)	894	1.8	6.2	Packaging (non-food)	Plastic
Metal bottle caps, lids and pull tabs from cans	700	1.4	4.4	Food and drinks	Metal
Plastic packaging for tobacco	649	1.3	5.2	Tobacco	Plastic
Drink lids	623	1.2	4.6	Food and drinks	Plastic
Diapers and wipes	588	1.2	3.5	Sanitary	Plastic
Lids and cap rings from plastic bottles	541	1.1	4.0	Others	Plastic
Aluminum foil	521	1.0	3.3	Food and drinks	Metal
Plastic food containers	448	0.9	3.4	Food and drinks	Plastic
Others lids	423	0.8	3.1	Others	Plastic
Shotgun cartridges	391	0.8	2.9	Others	Plastic
Foam items and pieces (not insulation)	335	0.7	2.3	Others	Plastic
Fireworks (rocket caps, exploded parts and packaging)	301	0.6	2.1	Others	Plastic
Plastic bags and pieces	285	0.6	2.0	Food and drinks	Plastic
Lids for chemicals and detergents	257	0.5	2.0	Others	Plastic
Labels and bar codes	252	0.5	1.9	Others	Plastic
Tissues, toilet paper and paper towels	241	0.5	1.9	Sanitary	Paper
Ceramic tile and pieces	231	0.5	1.5	Industry	Glass
Sanitary pads, tampons and applicators	215	0.4	1.9	Sanitary	Plastic
Plastic sheeting for large cargo items	160	0.3	1.2	Industry	Plastic
Foamed EVA	158	0.3	1.1	Others	Plastic
Glass and ceramic fragments (>2.5 cm)	145	0.3	0.8	Others	Glass
Construction materials (bricks, pipes, cement)	125	0.2	0.7	Industry	Glass
Fireworks (paper parts)	124	0.2	1.0	Others	Paper
Paper packaging	121	0.2	0.8	Packaging (non-food)	Paper
Clothing and rags	118	0.2	0.7	Others	Cloth
Ribbons and bows	84	0.2	0.7	Others	Plastic
Pellet mass	34	0.1	0.1	Industry	Plastic

Code and data availability. All the data and code used for this analysis are available at: XXX. The entire dataset and scripts related to the Identification, quantification and analysis of Swiss litter (IQAASL) project are publicly available at: https://github.com/hammerdirt-analyst/IQAASL-End-0f-Sampling-2021. An online report is available at: https://hammerdirt-analyst.github.io/IQAASL-End-0f-Sampling-2021/intro.html

Author contributions. RE conducted the principal analysis and designed the study. LS drafted the manuscript. LS and RE prepared the figures. RE, SE and BLS were responsible for the data collection. MF, YM and TvE edited and reviewed the manuscript.

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