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Plastic plants: Detecting riverine vegetation patches from space as proxy for marine plastic sources

Executive Summary Report

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Rationale

Vegetation may act as a sink for plastics, but the relationship between riverine plastic and plants remains unclear as most studies have focused on coastal ecosystems (Brennan et al., 2018; Cozzolino et al., 2020; Ivar do Sul et al., 2014; Martin et al., 2019; Olivelli et al., 2020). Indeed, results from the first study investigating riverine macroplastic seasonality suggested that water hyacinths act as a key driver of macroplastic transport in the Saigon river, Vietnam. Water hyacinth is a macrophyte species native from the Amazon, which has spread to most freshwater ecosystems in the tropics and subtropics (Thamaga & Dube, 2018). Water hyacinths are aquatic weeds that tend to form large patches floating at the water surface (several meters of width and length) in which important quantities of debris can get entrained (Figure 1). They are considered one of the most invasive vegetation species in the world, and are nowadays commonly found on all continents (CABI, 2020; IUCN, 2017).

Figure 1. Examples of floating macroplastic accumulation in hyacinth patches.

Most of the current earth observation satellites collect data at spatial and spectral resolutions too coarse or direct and accurate riverine plastic monitoring. However, larger sinks and accumulation zones of floating macroplastic, such as wood jams, aquatic and/ or riparian vegetation patches, might be detectable by satellite (Marcus et al., 2003, Schaepman et al., 2007; Smikrud and Prakash, 2006), offering an opportunity for quantifying plastic densities and transport rates.
Indeed, combining coverage estimates of these aggregation proxies using satellite-based detection with in-situ measurements of plastic densities might result in accurate first-order estimates (Figure 2). In this project, we explored the use of an indirect satellite-based approach to ultimately estimate plastic densities and transport rates in rivers.

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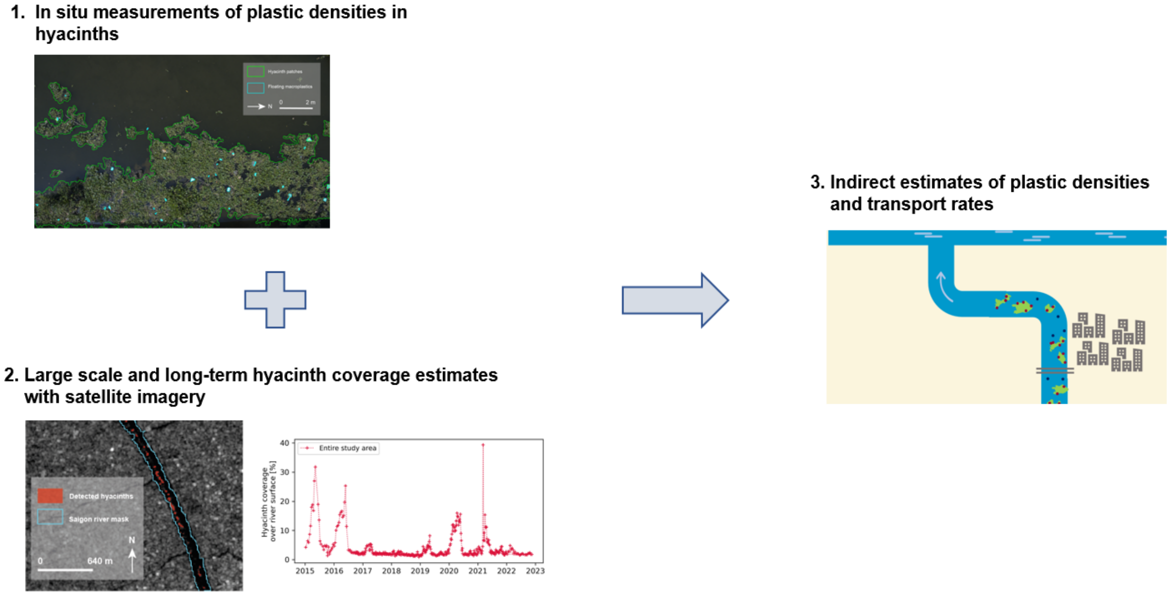

Figure 2. Workflow for indirect satellite-based approach to estimate plastic densities and transport rates, using hyacinth coverage estimates and in-situ measurements.

1. Project goal

The goal of this project is to explore **opportunities of plastic monitoring by using aquatic vegetation as a proxy**. For this, we aimed to:

(1) Understand the role of hyacinths (one of the world's most invasive aquatic vegetation species) in plastic transport in rivers.
(2) Develop an indirect approach to estimate plastic densities and transport rates, combining the detection of hyacinths from space with in-situ measurements.

Through in-situ measurements, we demonstrated that hyacinth patches function as (temporary) sinks for floating macroplastics. We further characterized the spatiotemporal distribution of plastic and hyacinths in the Saigon river with field-based observations. We explored direct satellite-based detection of river plastics and showed its limitations. Because of those, we instead developed the indirect approach abovementioned, combining both satellite-derived estimates of hyacinth coverage with in-situ measurement of plastic densities within hyacinths. Ultimately, we were able to provide a first-order estimate of plastic transport rates and river plastic densities.

Hyacinth patches are (temporary) plastic sinks

- Hyacinth patches transport 55-65% of floating macroplastic (one year average).
- Hyacinth plastic densities are 10 times higher than river surface plastic densities.
- The highest plastic density found in hyacinths is 190 times higher than the top plastic density measured in the Great Pacific Garbage Patch, and was measured for plastic trapped in hyacinths.
- Hyacinth entrains and traps plastics larger in size compared to items floating freely at the river surface.
- Differences in composition and size of plastic items inside and outside hyacinth patches are highly relevant for remote sensing applications because of the spectral characteristics and spatial resolution limitations of current satellite sensors.

Spatiotemporal distribution of plastic-hyacinth patches in the Saigon river with in-situ measurements

- At the two monitored sites, hyacinth coverage correlates strongly and significantly with plastic transport (Spearman $\rho=0.86$, $p\text{-value}<0.05$) on monthly scales.
- The temporal lag observed between (I) plastic transport and (II) accumulation processes (of hyacinth and plastic) demonstrates that plastic transport is best predicted on wider time-frames than the daily scale, such as monthly scale.
- Freely available, high-resolution satellite imagery collected by Sentinel-1 and Sentinel-2 are suitable for generating monthly estimates of hyacinth coverage (indirect plastic proxy), given the overpass frequency of these satellites.
- Within a 30 km section of the Saigon river, plastic fluxes were found to be 3-4 times higher downstream than upstream. Similarly, plastic densities were found to be 10 times higher downstream than upstream.
- Hyacinth coverage decreases by a factor of 15 downstream compared to upstream of the river, and patches become twice as small, due to increased river flow, boat traffic and salinity concentrations.
- The smaller size in patches in the downstream sections (< 0.8 m^2 on average) of the river make the accuracy of remote sensing based hyacinth coverage estimates more challenging at these locations.
- The lowest hyacinth coverage in the downstream sections of the river delineates a clear limit to the use of hyacinth coverage estimates to derive plastic transport rates for these sections of the river.

Comparing direct and indirect satellite-based estimates of river plastic densities

- Spectral bands in the 'Red' (central wavelength: 660.4 nm) and 'Red Edge' (central wavelength: 732.2 nm) are demonstrated to be suitable for the detection of river plastics.
- Estimates of riverine plastic loads using direct detection were three orders of magnitude lower than the estimates generated using an indirect sensing approach (5.8×10^1 items km^{-2} and 2.1×10^4 items km^{-2}, respectively, for the same day), a likely result of the spatial resolution limitation of satellite sensors.
- Future remote sensing systems should provide a spatial resolution at the centimetre scale for direct detection and counting of plastic items, given that most items are below 1 m in size and 50% of items found are below 5 cm in size. For satellite systems, use of panchromatic bands could help in reaching the centimetre scale. Other solutions entail establishing statistical relations between the presence of larger items (directly detectable with VHR sensors, at the meter scale) and smaller items (e.g.: 2-3 cm of size).
- Direct detection of river plastic by satellites is technically possible for larger items or concentrations of plastic items high enough to provide a detectable signal (i.e. when they cover a fraction of the area defined by the satellite Ground Sample Distance large enough to be detectable on the basis of the sensor sensitivity), but opportunities are still limited for current missions. Indirect detection methods are therefore promising alternatives to fill the gap.
- Hyacinth patches function as accumulation hotspots of macroplastics, given the higher plastic densities consistently found in hyacinths than at the river surface. Object detection and therefore precise quantification of item counts is currently only feasible with UAVs. Satellites could exploit the radiometric information contained in pixels to assess the probability of presence of plastics, and therefore detect/quantify accumulation hotspots in rivers by using hyacinths.

Spatial resolution challenges for direct satellite-based detection of riverine floating macroplastics

- Preliminary tests based on UAV images at very high resolution (e.g.: millimetre scale) show that the downscaling of such images to VHR (very high resolution) satellite imagery resolution (e.g.: centimetre to meter scale) largely results in the 'missing' of the majority of items. This is in line with the size distribution of floating macroplastic items, with 50% of items found to be below 5 cm in size.
- Such tests were done using only RGB UAV images, and multispectral VHR sensors would likely perform best for the detection of floating items, thanks to the added spectral band information into the red edge, near infra-red, and possibly shortwave infra-red.

Estimating hyacinth coverage with Sentinel-2

- Water hyacinth coverage over the Saigon river showed high temporal variability. The daily minimum and maximum coverage over the three year period monitored [2018-2020] and 60 km of river length varied by an order of magnitude of four (2×10^{-2}–2×10^{2} ha), monthly averages by an order of magnitude of two (1×10^{0}–1×10^{2} ha) and annual averages by a factor of five (1×10^{1}–5×10^{1} ha).
- Hyacinth coverage is higher during the dry season than during the wet season. During the dry season, the conditions for the proliferation of the plants (e.g.: lower river flow, higher water stability and higher nutrient concentrations) are met, favouring the development of large blooms. During the wet season, higher flow velocities likely destabilize patches and flush them further in the downstream direction.

Estimating hyacinth coverage with Sentinel-1

- Similar to the estimates of hyacinth coverage obtained with Sentinel-2, we found that hyacinth coverage is higher during the dry season (Dec-May) than during the wet season (Jun-Nov) over the eight year monitored period (2015-2022).
- Hyacinth coverage decreases along a longitudinal gradient over the studied area, probably due to the break-down of patches due to boat traffic, higher flow velocities and salt concentrations.

Combining hyacinth coverage and hyacinth plastic densities estimates to derive river plastic loads

- We estimated river surface plastic densities at 1.1×10^{5} items km^{-2} for a 11 km^{2} area of the Saigon river. This is within the range of our in-situ measurements. This is equivalent to 0.6-1.1 tonnes km^{-2}, considering an average mass per item of 5-10 g $item^{-1}$.
- In line with previous results, we found that the downstream sectors have higher river surface plastic densities than the upstream Saigon river areas.
- We derived plastic transport values, using averaged flow velocities for the ebb (seaward) and flood (landward) phases of the tidal cycle. We found that estimates of plastic transport (in the order of magnitude of 10^{4} items $hour^{-1}$) using this indirect satellite-based approach are within the same range than those derived from in-situ measurements for the downstream area. For the upstream area, plastic transport estimates were found to be lower than those directly measured, by a factor ranging between 2 to 7, depending on the flow direction.

2. Synthesis

Our findings demonstrate that water hyacinths, the world's most invasive aquatic plant, play a crucial role in transporting and accumulating riverine macroplastics. Firstly, patches of hyacinth transport the majority of floating macroplastic, with little variation depending on the monitored sites. On average, 55-65% of floating macroplastic is transported within hyacinth patches. As a consequence, plastic densities are on average 10 times higher in hyacinth patches than floating free on the river surface. Secondly, plastic transport and densities, and hyacinth coverage itself, all exhibit a clear seasonality over the monitored river (Saigon river, Vietnam), with highest abundances during the dry season (Dec-May). As a result, hyacinth coverage correlates strongly and significantly with plastic transport (Spearman $\rho=0.86$, p-value<0.05) at a monthly scale. This last point highlights that monthly averaged hyacinth coverage estimates could be suitable predictors for estimating riverine plastic transport. Thirdly, plastic densities and plastic transport were found to be higher downstream than upstream; whereas an inverse trend was observed for hyacinth coverage. This emphasizes both the need to account for the spatial variability in plastic densities along the river and the practical challenge in detecting smaller hyacinth patches with remote sensing. Overall, these elements demonstrate the relevance of using hyacinth as proxies for plastic load estimates in rivers, provided the spatial variability in plastic densities is accounted for.

Our remote sensing approaches showed the feasibility in developing indirect remote sensing methods for estimating river plastic loads based on relevant proxies for plastic pollution. We applied an indirect sensing approach by using water hyacinth as the proxy for floating macroplastic in the Saigon river, Vietnam. Hyacinth coverage can be estimated with freely available remote sensing products, such as Sentinel-2 and Sentinel-1. Similarly to what found through in-situ measurements, hyacinth coverage followed a clear seasonal pattern, with higher coverage during the dry season than during the wet season. During the dry season, the conditions for the proliferation of the plants (e.g.: lower river flow, higher water stability and higher nutrient concentrations) are met, favoring the development of large blooms. In addition, we found that hyacinth coverage decreases along a longitudinal gradient over the studied area, probably due to the break-down of patches due to boat traffic and higher flow velocities. Ultimately, we combined remote sensing estimates of hyacinth coverage with in-situ measurement of hyacinth plastic densities, in order to derive river plastic densities and plastic transport rates. We found transport rates in the order of 10^4 items hour^{-1} for both seaward and landward flow, and plastic densities in the order of 10^4 items km^{-2} in the upstream area and 10^5 items km^{-2} in the downstream area of the studied river. For both river plastic densities and transport, our estimates are within the same order of magnitude than our estimates derived from in-situ measurements. This is ultimately a better achievement than plastic loads estimates based on direct sensing approaches. Direct sensing of floating macroplastic was tested but resulted in river plastic densities lower by three orders of magnitude than those found with the indirect approach and by in-situ measurements.

Overall, in the Saigon river, peaks in hyacinth tend to correspond to peaks in plastic densities and transport in downstream regions. Therefore, it is likely that peaks in hyacinth coverage also indicate peaks in plastic exports from rivers into the ocean.

3. Recommendations

Based on the findings of our projects, we elaborate a series of recommendations for future work, with a focus on the opportunities and challenges in using remote sensing to tackle the plastic pollution problem. We categorized our recommendations into the following three groups:

a) fundamental: aspects that pertain to scientific questions that are still unresolved and require different approaches than those used throughout this project;
b) practical: elements related to gaps in knowledge due to limited resources and/or time in answering those and that typically require expanding the approaches developed for the purpose of this project;
c) transferability/scalability: elements that specifically relate to the transferability of our findings to other rivers.

Considering the role of hyacinths as plastic sinks we formulate the following four main recommendations:

1) Investigate the root causes explaining the relation between plastic and hyacinth abundance. The strong and significant correlation found between the abundance of hyacinth on the one hand, and the abundance of plastic on the other hand, does not indicate whether the two derive from the same causes. It is still unclear whether hyacinths can be considered opportunistic proxies, or if peaks in hyacinth invasion can be also related to human activities that lead to high river plastic input rates. One hypothesis pertains to the hydrological cycle. During the dry season, the lower net river discharge results in both i) higher nutrient availability and concentrations, with facilitate hyacinth proliferation ii) higher abundance of plastics, due to the lower net downstream transport (less 'flushing' of items out of the river system) (**Recommendation 1, fundamental**).
2) Investigate the release time and location of plastics previously entrapped in hyacinths once patches disintegrate in the river. The life-cycle of plastic items within the river system is still unknown, and the fate of items previously trapped in hyacinth patches remains unclear. This is particularly relevant to understand transfer dynamics from the riverine area to the estuarine area, and thus to better investigate plastic emissions into the ocean (**Recommendation 2, fundamental**).
3) Further quantify the spatial variability in plastic loads (densities and transport) and in hyacinth coverage. Our project only investigated the spatial variability through in-situ measurements at two locations. The spatial component is the most significant aspect in variability for all the variables investigated (e.g.: hyacinth coverage, plastic transport and plastic densities), and therefore additional in-situ measurements at various locations along a longitudinal gradient would be beneficial for better understanding the relation between hyacinth and plastic spatial distribution (**Recommendation 3, practical**).
4) Extend similar data collect efforts to rivers for which there is preliminary evidence of similar relation between hyacinth and plastic. We have anecdotical evidence that hyacinths play an important role in accumulating large quantities of floating macroplastic in other highly polluted rivers around the world: the Vam Co Dong river in Vietnam, the Ozama river in the Dominican Republic, the Chao Phraya river in Thailand and the Citarum river in Indonesia. (**Recommendation 4, scalability**)

Considering the opportunities for developing remote sensing based techniques to estimate plastic loads in rivers, we formulate the following recommendations:

1) Investigate the detectability of riverine plastics with sensors with meter-resolution scale and covering both the NIR and SWIR range. Recent advances in the field of plastic remote sensing indicated the relevancy of using sensors in the NIR and SWIR range of the electromagnetic spectrum (Biermann et al., 2020; Tasseron et al., 2021; Guo and Li, 2020). Our in-situ measurement showed that the size distribution of riverine plastic items is mainly suited for direct detection with sensors with spatial resolution at the centimetre scale resolution, considering only the visible range. Multispectral sensors covering up to the SWIR range might help in tackling this spatial resolution 'bottleneck'. The hyacinths represent an "anomaly" in the river that can be more easily identified with remote sensing and consequently they represent a strategic target to focus on with remote sensing tools, including next generation satellites, to directly detect the trapped plastic items, which, compared to plastic items floating at the river surface, have been shown to be at higher concentrations, so more detectable, and often drier and consequently more visible also at longer wavelength, e.g. in the SWIR (**Recommendation 5, fundamental**).
2) Expand the validation of Sentinel-1 detection approach for hyacinth coverage estimates. We did not fully validate the detection of hyacinth patches with Sentinel-1 SAR imagery. This could be explored by using VHR satellite imagery for validation or in-situ measurements of hyacinth coverage. Apart from our specific application, the detection of riverine invasive plants using SAR

imagery is particularly relevant due to the widespread presence of such species in tropical waterways, in regions with high cloud coverage. The use of SAR technology for invasive plant monitoring in waterways is still relatively unexplored for long-term monitoring, despite the need for monitoring tools (**Recommendation 6, practical**).

3) Explore the use of other relevant proxies for riverine plastics that can also be detected from space, especially during high accumulation events. Recent research shows that plastics accumulate in wood jams at much higher densities than otherwise found in the river (Liro et al., 2022). In addition, extreme events such as floods favor both the mobilization of plastics within the river system and their deposition on riverbanks (van Emmerik et al., 2022c). A remote sensing based approach could use relevant proxies for the identification of accumulation zones during specific events that mobilized high debris flows (**Recommendation 7, scalability**).

4. Scientific project output

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