The effect of China's plastic waste import ban on plastic waste leakage into the aquatic environment

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By

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Author's Declaration of Originality

I hereby certify that I am the sole author of this thesis. All the used materials, references to the literature and the work of others have been referred to. This thesis has not been presented for examination anywhere else.

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Abstract

Many higher-income countries export plastic waste to lower and middle-income countries where treatment facilities are often less advanced, which therefore comes with greater environmental consequences. China was the largest importer of plastic waste until it issued the Prohibition of Foreign Garbage Imports (referred to as "the China import ban") in 2017, which drastically changed global plastic waste trade. This study uses country-level data on waste management, and trade statistics combined with high resolution sub-national population density maps to assess the effect of the China import ban on plastic waste leakage into the aquatic environment. The results are presented on a 30-arc grid (approximately one km^2) resolution. Global mismanaged plastic waste (MPW) generation is estimated to increase from approximately 62 Mt (million ton) in 2016 to 64.7 Mt in 2019. Around 64% is emitted into the aquatic environment, which is estimated to increase from approximately 39.5 Mt in 2016 to 41 Mt in 2019. MPW emission into the aquatic environment from imports accounted for approximately 1.9% of global emission in 2016 and decreased to 1.4% in 2019, which is the result of a 43% reduction in global traded plastic waste. Despite the substantial decrease in Chinese aquatic MPW emission from imports, other lower or middle-income countries with higher rates of mismanagement and a higher probability of emission experienced strong increases.

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1. Introduction

The use of plastics in the consumer marketplace has experienced exceptional growth since its start around 1940, and reached a global annual production of more than 300 million metric tons (Mt) in recent years[1][2]. This is an increase of more than 600% since 1975. Plastics became a widely used product for its societal benefits such as its low-cost, easily formable, hydrophobic and bio-inert characteristics[3]. Its largest market sector is consumer packaging, of which 42% consists of plastic resins[4].

Increased plastic usage is accompanied with a global increase in plastic waste. Whereas plastics accounted for less than 1% of municipal solid waste in the United States around 1960 [5], this number increased to a minimum of 10% in more than half of the 105 countries with available data in 2005 [6]. Earlier research estimated that urban regions will generate at least 6 Mt of solid waste per day in 2025[7]. With a 10% fraction, this results in more than 200 Mt for the whole year. This is as much plastic waste as the total global plastic production in 2002[8].

Plastic waste can be divided into two fractions: managed plastic waste and mismanaged plastic waste (MPW) [4]. Earlier research defined MPW as "material that is either littered or inadequately disposed" and also states that "inadequately disposed waste is not formally managed and includes disposal in dumps or open, uncontrolled landfills, where it is not fully contained" [1] (p.768).

Previous research concluded that 80% of marine debris came from land since discharges from at-sea vessels became prohibited after a 1975 estimation of the annual marine litter flux[1]. Since this percentage did not properly reflect the total amount of plastic waste leaking from land into the marine environment, earlier research "estimated the annual input of plastic to the ocean from waste generated by coastal populations worldwide"[1] p.768. The study resulted in an estimated 275 million Mt of plastic waste of which between 4.8 and 12.7 million Mt ended up in the ocean in 2010. Other research estimated that annual plastic waste emissions into the marine environment lay between 1.2-2.4 Mt, and 0.8-2.7 Mt, respectively[9][10].

Data-driven insights are required for the implementation of local policies aimed at the mitigation of MPW ending up in the marine environment[2]. However, earlier research stated that the estimates at the time were inadequate to determine regional mitigation measures as plastic waste generation on a country level is spatially heterogeneous[1][2]. For example, 97% of the projected population growth until 2025 is expected to take place in regions where plastic waste ending up in the environment is relatively high[2]. In order to better understand the spatial variance on a regional and country-level, Lebreton Andrady (2019) aimed to create higher-resolution maps with finer granularity than previous studies had accomplished. Both studies had two major limitations in common. Firstly, the estimated mass of MPW input to the oceans consisted of a broad range of 15% to 40%. Secondly, the international plastic waste trade was not included in the models[1][2].

Since the late 1990s, the export of plastic waste from high-income countries to low-income countries has become a common practice as for environmental risks and economic benefits[11]. Although plastic waste imports offered a wide range of opportunities for low-income countries, it also caused severe environmental impacts due to the less advanced treatment methods and technologies. Exporting plastic waste to low-income countries comes therefore with a greater environmental impact than treating it in a high-income country[11].

Adding international plastic waste trade to previous models will provide better insights into the origin of MPW and could allow for country-specific incentives to reduce exports to lower-income countries[1][2].

Before mid-2017, more than 55% of global plastic waste was exported to China[11]. However, as 70% of these imports were buried or mismanaged, and therefore causing environmental problems, China issued the Prohibition of Foreign Garbage Imports (referred to as "the China import ban") in 2017[12]. One of the types of solid waste imports which was now banned was plastic waste. As a result, the international plastic waste trade structure changed drastically, and more plastic is now exported to other low-income countries with less advanced treatment facilities[13]. The research gap is that research should be conducted in order to assess the global environmental impacts as a result of the China import ban, such as plastic waste leakage into the marine environment[11]. However, plastic waste emissions do not only end up in the marine environment, but also accumulate in other parts of the aquatic environment, such as lakes and rivers[14]. Therefore, this study broadens the scope compared to earlier research into the aquatic environment, rather than only the marine environment. The aquatic environment in this study thus consists of the marine environment, lakes, and perennial rivers and streams. The latter are bodies of water with a minimal long term average discharge of 0.0 m^3s^{-1}, which are intermittent for less than one day per year[15].

In order to address the knowledge gap, this study aims to answer the following research question: *To what extent does China's plastic waste import ban affect global mismanaged plastic waste leaking into the aquatic environment?*

To answer this main research question, five sub-research questions are formulated that will allow this study to answer the main research question.

- To what magnitude did the international waste trade network change after the China import ban?
- Where is mismanaged plastic waste most likely to be emitted into the aquatic environment?
- Where did leakage of mismanaged plastic waste into the aquatic environment change after the China import ban?
- To what extent does leakage of plastic waste into the aquatic environment from plastic waste trade affect national plastic waste leakage statistics?
- To what extent does the probability of emission affect plastic waste leakage into the aquatic environment?

Based on previous literature and research this study hypothesizes the following:

The increased export of plastic waste to other lower of middle-income countries than China increases the amount of plastic waste ending up in the aquatic environment.

2. Methodology

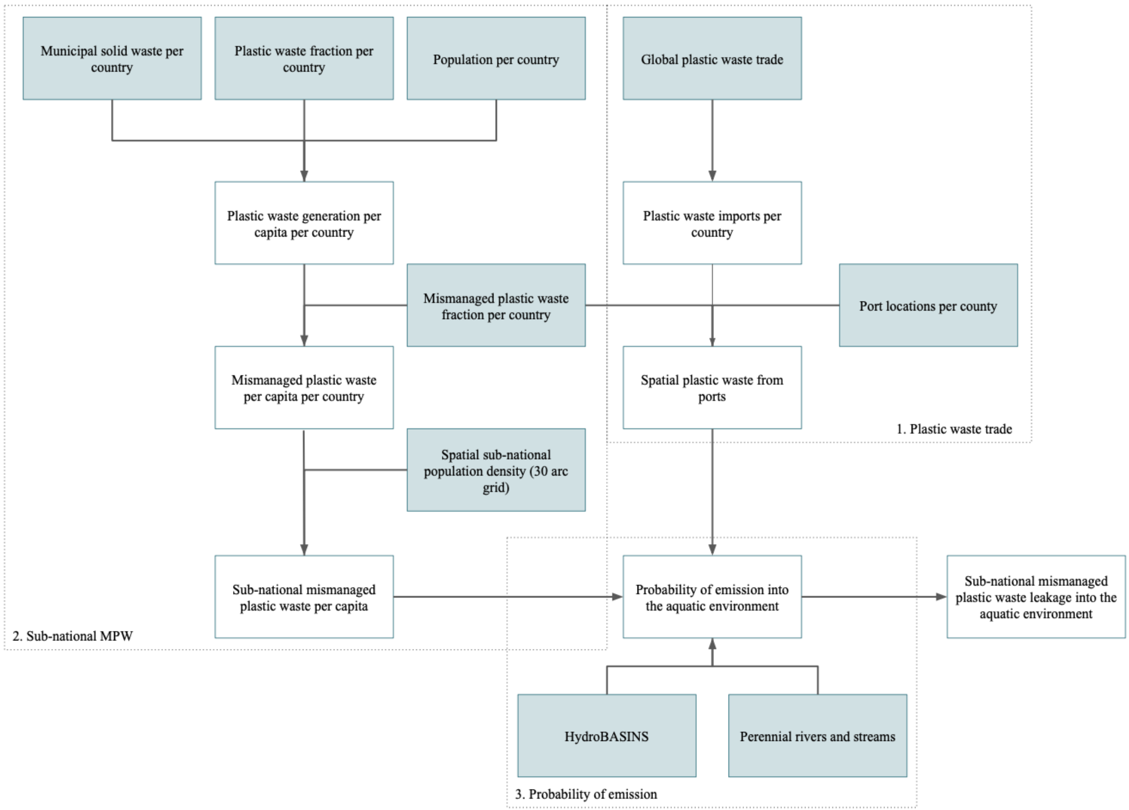

Figure 1. Flow Chart Diagram as a schematic overview of the quantitative model its structure. Blue boxes are data and input, and white boxes are modelling steps or processes.

A quantitative model is used to test the hypothesis and answer the main research question, and builds further on earlier research. The structure of the model as a flow chart diagram is shown in figure 1. The model can be divided into three main steps. The first step creates a map with MPW from ports, the second step creates a map with sub-national MPW per capita, and the third step creates a map with the probability of emission of MPW into the aquatic environment. The following sections discuss these three modelling steps, and how these come together in a fourth section.

2.1 Global plastic waste trade and MPW from ports

The first section of the model quantifies the amount of mismanaged plastic waste around ports per country. A model was built that determines the total imports, exports and net-imports per country or UN region. This model uses UN Comtrade data for 2016 and 2019[16]. The four product codes used to filter plastic waste trade are 391510 for PE, 391520 for PS, 391530 PVC, and 391590 for other plastic waste (including PET and PP). This modelling part is used to assess the key actors in the trade network and to assess how this network changed as a result of the China import ban. The imports and exports are then connected to the ports per country to determine the MPW around ports[17]. Imports are most likely processed in close proximity to the port to minimise transportation costs[18]. Therefore, the amount of plastic waste is equally distributed in a range of 50 km around each port. Equation 2.1 shows the MPW emission into the aquatic environment from ports after plastic waste is equally distributed.

$$MPW_{ports} = DPW \cdot MWF \cdot P(E) \tag{2.1}$$

where DPW is the distributed plastic waste, MWF is the mismanaged waste fraction, and $P(E)$ is the probability of emission. The latter two are discussed in the following paragraphs.

2.2 Sub-national MPW per capita

This second section could be considered to be an improvement of modelling steps from earlier research. Whereas [2] used municipal solid waste (MSW) data distributed by the Waste Atlas in 2016, extensive research found data from [19] to be more up to date and complete. This source also includes data regarding the plastic waste fraction, population per country, and waste disposal fractions in 2019.

The waste disposal fractions are used to determine the mismanaged waste fraction per country. Other research that used the What a Waste Database 1.0, considered all open dumps and landfills in low-income countries as mismanaged[1]. The most recent version (e.g. What a Waste Database 2.0) contains more waste disposal categories. In addition to open dumps and landfill, the *unaccounted for* percentage is also considered mismanaged as [20], assume that this percentage is dumped as well. However, other research made the assumption that an unspecified fraction should be a function of income level if no further information is available[18]. Therefore, the mismanaged fractions from the unspecified category considered are 75%, 50%, 25%, and 0% for lower, lower-middle, upper-middle, and higher-income levels, respectively[18].

Table 1. Correlation between per capita GDP and three variables distributed by The World Bank.

Per capita GDP (2019 USD)	**Spearman' r**	**Spearman' p**	**n**
Per capita municipal solid waste (MSW) (kg per year)	0.82	**<0.005**	192
Mismanaged waste fraction (%)	-0.57	**<0.005**	118
Plastic waste fraction in MSW (%)	0.18	0.022	156

Data is not available for every country. To make this dataset as complete as possible, the different variables are compared to per capita GDP retrieved from the International Monetary Fund[21]. A Spearman correlation test for MSW, the plastic waste fraction and the mismanaged waste fraction was conducted. The results are shown in table 1.

Per capita MSW and the mismanaged waste fraction both have a significant correlation with per capita GDP. This confirms what earlier research already concluded: a positive correlation between per capita MSW and per capita GDP reflects a higher waste generation as a result of higher consumption levels in rich countries[2]. Secondly, the negative relation in the mismanaged fraction reflects that a greater amount of waste is unsoundly disposed in lower-income countries. The plastic waste fraction does not show a significant correlation with per capita GDP, which suggests that the amount of plastic waste in MSW is not related to the per capita GDP.

The data gaps in MSW and the mismanaged fraction are filled with a k Nearest Neighbour (kNN) algorithm. The kNN algorithm is a non-parametric or an instance-based method to fill up data gaps[22]. It essentially labels the most similar samples within the same class as the most probable to fill up the missing value. By finding the k nearest neighbours with similar values, it determines the value to fill the gap. Selecting k is best done by taking the root of n in case of more than 100 samples[22].

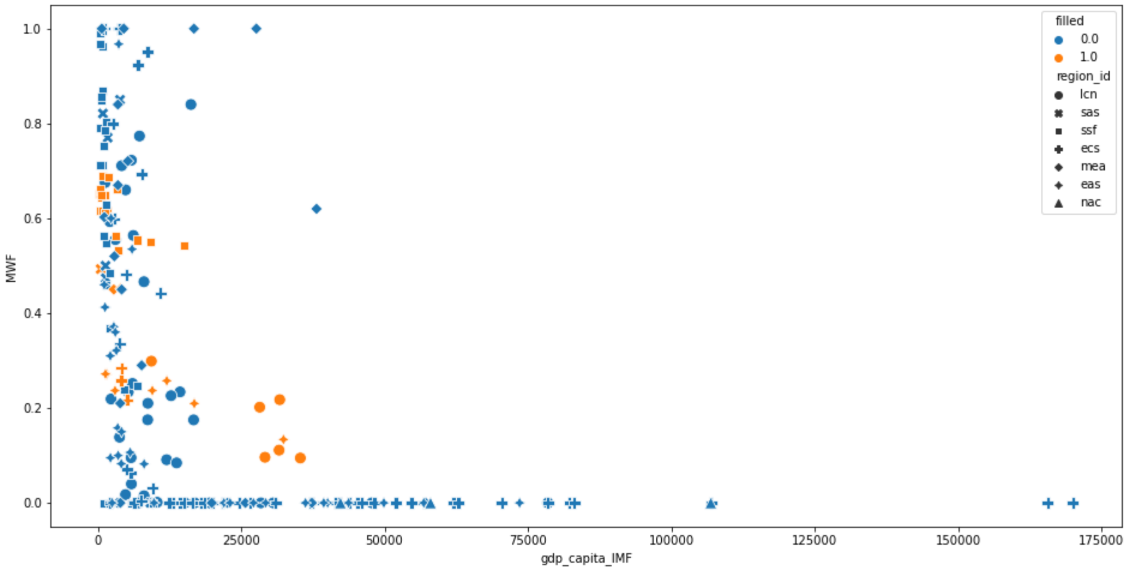

Figure 2. Filled data gaps in the mismanaged waste fraction (MWF), where orange markers are filled with the kNN algorithm. The X-axis is the gross domestic product (GDP) per capita[21]

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The countries are first separated based on geographic region and are then sorted based on total GDP per country. Countries are sorted based on total GDP rather than per capita GDP as some countries skew overall results of the kNN algorithm. As an example, Monaco its GDP per capita is the highest globally, but its total GDP ranks 152th out of 216 countries in the dataset[21]. A repetitive process showed better results with total GDP. The result for the mismanaged waste fraction is shown in figure 2. The data gaps in the plastic waste fraction are filled with data from earlier research[2]. Using the kNN algorithm and data from earlier papers results in a total number of 212 countries.

The What a Waste Database 2.0 reports a zero percent mismanaged waste fraction for many high-income countries[19]. An additional littering factor is included to account for unreported litter. Plastic littering research is difficult to generalise to global statistics since it often reports counts of specific items, rather than total mass[1]. Additionally, generalising presented research to global statistics comes with great levels of uncertainty[2]. This study therefore takes the same approach as presented in earlier research[1]. Based on [23][24], approximately 2% of the national waste in the United States was littered in 2008. The assumption is made that this number represents the litter fraction in high-income countries. Most middle and lower-income have a mismanaged waste fraction greater than 2%. The What a Waste database 2.0 reports for some of these countries a mismanaged waste fraction of 100%. The assumption is made that the countries with a mismanaged waste fractions greater than 2% already include the littering fraction.

The mismanaged plastic waste generation per capita is determined by multiplying MSW, the plastic waste fraction, the mismanaged waste fraction and dividing by the population, as shown in equation 2.2.

$$MPW_{capita} = \frac{MSW \cdot PWF \cdot MWF + Litter}{p} \tag{2.2}$$

where MSW is municipal solid waste per country (in tons), PWF is the plastic waste fraction per country,

MWF is the mismanaged waste fraction per country, and p is population. This MPW per capita per country data is then multiplied with a subnational population density raster for 2016 and 2019[25]. The result is a 30 arc-second raster (approximately one km^2 at the equator) with the mismanaged plastic waste per capita per year in tons.

2.3 Probability of emission into the aquatic environment

The probability of emission is a distance-based function that determines the chance of on-land MPW being emitted into the closest aquatic environment. The aquatic environment is defined as the marine environment, lakes and perennial rivers and streams. Perennial rivers and streams are bodies of water with a minimal long term average discharge of 0.0 m^{3}s^{-1}, which are intermittent for less than one day per year[15].

Earlier research defined a probability of intermittence for 64 million kilometres of rivers and streams across the globe (except for rivers and streams below and above the 60° south and north latitudes)[15]. A river or stream is 100% perennial if there is a 0% probability of intermittence. There is a rather small share of rivers and streams which have a 100% probability to be perennial (e.g. 47 river segments out of almost 1.4 million have an intermittence probability of 0.0% in Asia). Therefore, the binary flow intermittence class with a probability threshold of 50% was used to select perennial and non-perennial rivers and streams[15]. Each river segment has a unique ID (HYRIVID), which can be used in accordance with HydroRIVERS and HydroBASINS data[26]. After filtering all perennial rivers and streams, the HYRIVIDs can be used to find the corresponding level 12 river basin ID (HYBASID), which are labelled as a perennial basins. The HydroBASINS data provides the distance from each basin to the most downward sink, which is the outlet of the river basin. This distance is measured in kilometres and follows the river network it is part of. Equation 2.3 is used to calculate the distance of each basin to the closest downward perennial basin.

$$D = DISTMAIN_i - DISTMAIN_p \tag{2.3}$$

where $DISTMAIN_i$ is the distance from each basin to the outlet of the river basin, and $DISTMAIN_p$ is the distance from the first perennial basin along the river network of $DISTMAIN_i$ to the outlet of the river basin.

A previous study made the assumption that MPW generated more than 100 km away from a downstream aquatic ecosystem is likely discarded and does not end up in the aquatic environment[27]. Besides perennial basins, MPW could also end up in the marine environment which is not labelled as a perennial basin. A distance matrix is therefore used to determine the distance of each level 12 basins to the closest coastline. To determine the probability of MPW being emitted into the aquatic ecosystem, the following equation is used.

$$P(E) = 1 - U \cdot log_{101}(D + 1) \tag{2.4}$$

where $P(E)$ is the probability of MPW originating in a level 12 river basin that drains according distance D into the aquatic environment. U is a random variable retrieved by using a uniform distribution interval between 0.9 and 1.0[27]. Distance D is the shortest distance to either a perennial basin or a coastline.

2.4 Direct and non-direct re-export scenarios

The analysis consists of a baseline year before the China import ban and the most recent year after the China import ban (e.g. 2016 and 2019) to make a comparison between MPW emission into the aquatic environment. Additionally, the model is used in two different ways - direct and indirect re-exports. Due to limited availability or strongly diverging data on waste fractions in 2016[2], this study assumes the municipal solid waste generation, plastic waste fraction and mismanaged waste fraction to be the same in 2016 and 2019. The impact of the China import ban on the emission of MPW into the aquatic environment becomes clear by keeping this data similar for both years.

Direct re-exports

In the scenario with direct re-exports, imports are not leaked into the aquatic environment before potentially being re-exported. The assumption is made that only countries with net-imports leak plastic waste near ports, and that countries with net-exports do not leak any plastic waste from ports, even if the country imports plastic waste. The assumption is therefore also made that all imports get re-exported if the exports are higher than imports. The difference between exports and imports, or net-exports, for exporting countries is retrieved from domestic produced plastic waste, PWF, taking into account the mismanaged waste fraction. The assumption is made that all domestic produced plastic waste is evenly likely to be exported, despite distance to the port or collection in urban or rural areas. Equation 2.5 is a sanity check for net-exporting countries to determine if the remaining PWF after mismanagement with addition of imports provides enough for the difference between exports and imports. Equation 2.6 determines how much PWF is missing in the mass balance if exports cannot be provided. As [20] and UN Comtrade data is reported for a single year without existing stock, a mismatch in the mass balance could occur.

$$export > PWF \cdot (1 - MWF) + import \tag{2.5}$$

$$PWF_{missing} = \frac{export - (PWF \cdot (1 - MWF) + import)}{(1 - MWF)} \tag{2.6}$$

PWF is the domestic produced plastic waste fraction, and MWF is the mismanaged waste fraction. For this scenario, equation 2.7 and equation 2.8 calculate the total emission for net-exporting and net-importing countries, respectively.

$$emission_{export} = MPW_{capita} \cdot p \cdot P(E) \tag{2.7}$$

$$emission_{import} = (MPW_{capita} \cdot p + (import - export)) \cdot P(E) \tag{2.8}$$

where p is population. For net-importing countries, imports are added to the total domestic produced mismanaged plastic waste including litter before multiplication with the probability of emission factor.

Indirect re-exports

In the scenario with indirect re-exports, imports are leaked before potentially being re-exported. Similar assumptions are made for this scenario, except for the assumption that now all imports could be leaked rather than only imports in net-importing countries. The sanity check as shown in equation 2.9 and 2.10 similarly determines if there is a mismatch in the mass balance. The equations differ as imports are added to the PWF before being subjected to the mismanaged waste fraction.

$$export > (PWF + import) \cdot (1 - MWF) \tag{2.9}$$

$$PWF_{missing} = \frac{export - ((PWF + import) \cdot (1 - MWF))}{(1 - MWF)} \tag{2.10}$$

For this scenario, equation 2.11 calculates the total emission for net-exporting and net-importing countries.

$$emission = (MPW_{capita} \cdot Population + import) \cdot P(E) \tag{2.11}$$

3. Results

3.1 Plastic waste trade

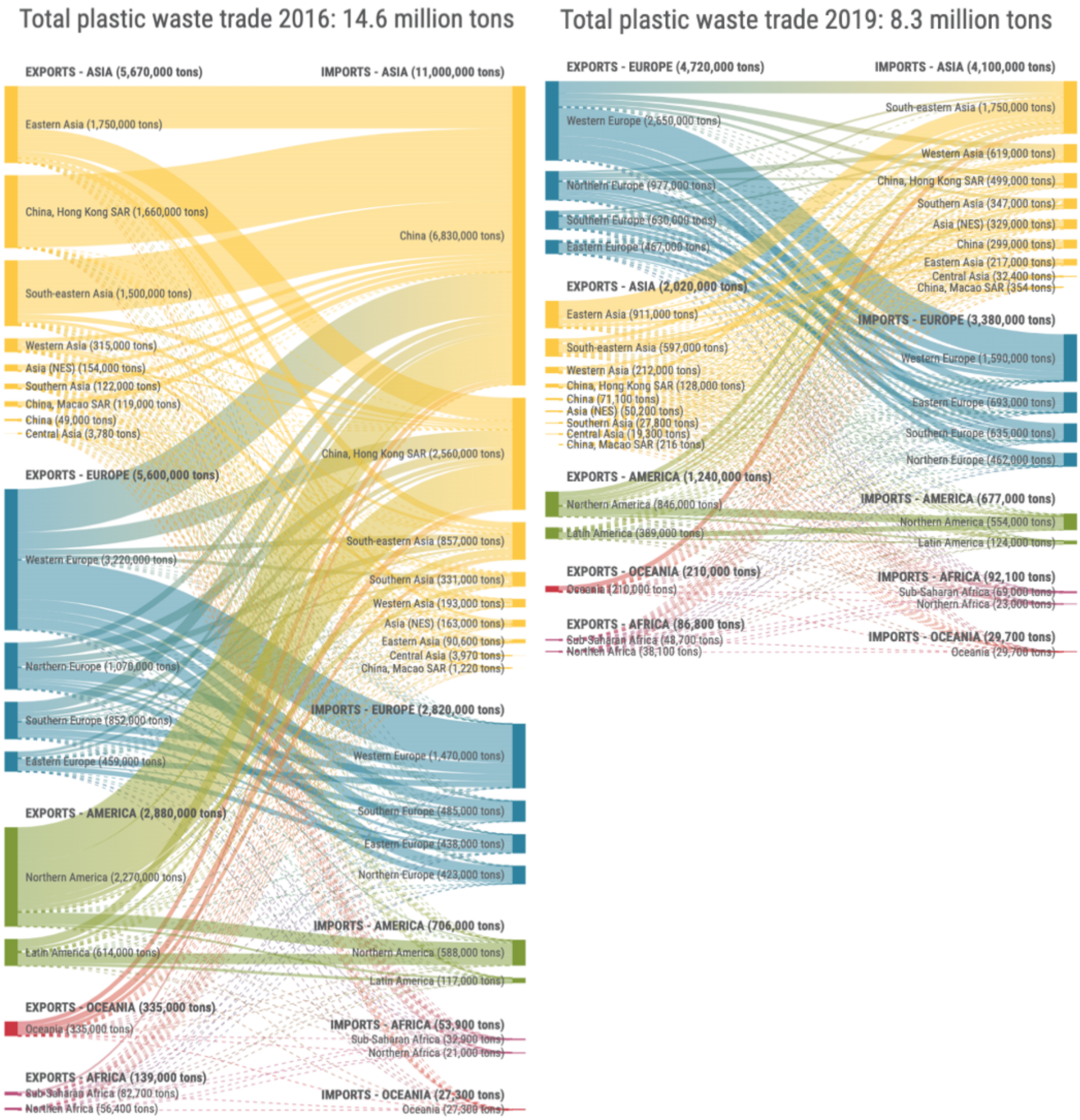

Figure 3. Sankey-diagram of the global plastic waste trade between UN regions, China, Hong Kong SAR, and Macao SAR. The years 2016 and 2019 are shown on the left and right, respectively. The Sankey-diagram was made with Metabolic B.V. its software.

The results in figure 3 show the total trade for the year before the China import ban (e.g. 2016) and the year after the China import ban (e.g. 2019). Whereas 14.6 million tons of plastic waste was exported in 2016, only 8.3 million tons was exported in 2019, which is a reduction of 43.1% (figure 3). According to earlier research, this may be a result of the China import ban[11]. A significant change in exports occurred in Asian exports, which decreased by more than 64%. A possible explanation is the similar decrease in total imports by China, Hong Kong SAR and Macao SAR, which together were responsible for more than 64% and 85% of global and Asian plastic waste imports in 2016, respectively. As shown figure 3, most Asian

Table 2. Net-imports per UN region in kilo tons (kt) for 2016 and 2019. Negative values represent net-exports

Region	**2016 Net-import (kt)**	**2019 Net-import (kt)**
Eastern Asia	5,896	-94
Southern Asia	209	319
Central Asia	0	13
Northern Africa	-35	-15
Sub-Saharan Africa	-49	21
Western Asia	-122	407
Oceania	-308	0
Latin America and the Caribbean	-497	0
South-eastern Asia	-641	1,154
Northern America	-1,678	-292
Europe	-2,784	-1,344

regions, export plastic waste directly to China or via Hong Kong SAR to China, which has been an important trade transfer stop towards the Chinese mainland[28]. This decrease thus shows that the primary focus of the China import ban (e.g. to decrease plastic waste imports) could be considered met[12]. Despite the drastic decrease in total Asian exports and imports, all imports in Asian UN regions - except for China, Hong Kong SAR and Macao SAR - increased significantly (table 2). This shows that other Asian countries are importing more plastic waste since the China import ban[29].

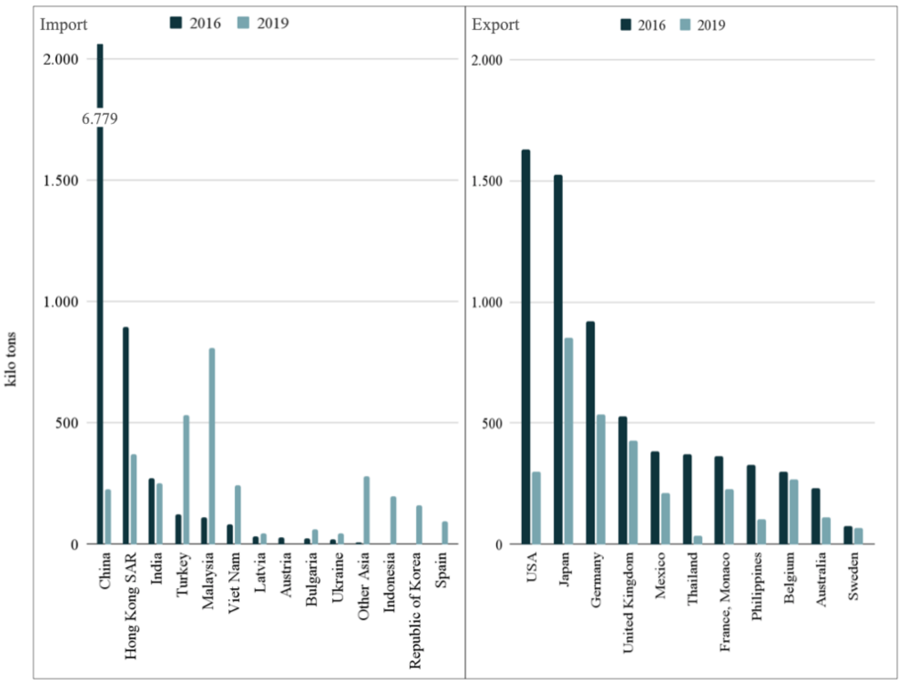

Figure 4. The top ten largest importers (left) and exporters (right) in 2016 and 2019.

Another notable change occurred in Northern American exports. Total exports from the Northern American region decreased by more than 82% (figure 4 and table 2). It exported 85% to Asian regions in 2016 and only 55% in 2019. Whereas American exports decreased significantly in total, European exports decreased by 15%, which for a large part consisted of export to Asian regions. This indicates that since the China import ban, Western regions now treat more of the plastic waste within the originating region[11]. Despite relatively small quantities, Northern Africa and Sub-Saharan Africa its imports increased by over 70%. The most significant change occurred in South-Eastern Asia which exported 641 kt in 2016 and imported 1,154 kt plastic waste in 2019 (table 2).

On a country-level basis some additional insights become clear from figure 4. Besides the significant decrease in imports by China in 2019, an increase in imports occurred in other Asian countries such as Turkey, Malaysia, Vietnam, Indonesia, and the Republic of Korea. Other than the ten largest importers, 53 importing countries accounted for 1.5% of total imports in 2016, and 83 countries accounted for 14.5% in 2019. This shows that whereas rather few countries were responsible for most imports in 2016, global plastic waste imports were distributed over more different countries in 2019[30].

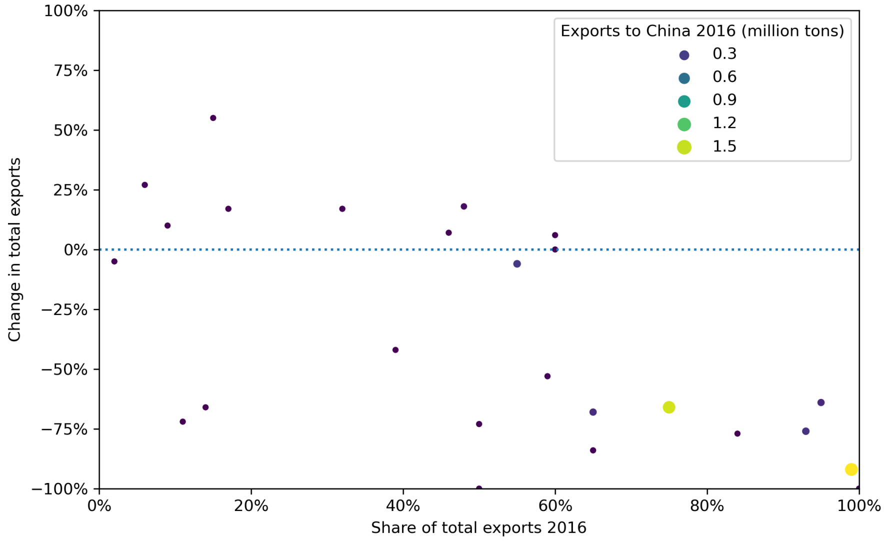

Figure 5. A scatterplot visualising the relation between change in total exports in 2016 and 2019 and the share of total exports to China, Hong Kong SAR and Macao SAR in 2016. The dots represent all countries that export plastic waste to China in 2016.

Countries with the highest share of its export going to China, Hong Kong SAR, and Macao SAR are most likely to experience a significant decrease in total exports after the China import ban (figure 5). However, the reduction in total exports is in most cases less than the share of plastic waste exports to China. This suggests that not all exports to China are treated in the country of origin, but are partially exported to other countries after the China import ban. The USA (including Puerto Rico and Virgin US Islands) and Hong Kong SAR experienced the largest absolute change. The former its total exports reduced by 66% and exports since the China import ban mostly to Canada and India. The latter was an important trade transfer stop towards the Chinese mainland [28] and has its exports reduced by over 90% since the China import ban.

3.2 Mismanaged plastic waste generation

By combining the country-level data with a high resolution sub-national population density map, and national plastic waste trade data, a 30 arc second map is created with mismanaged plastic waste generation for 2016 and 2019. The maps are created for the two scenarios per year (see supplementary materials). In the first scenario, imports are assumed to be re-exported directly for net-exporting countries, and in the second scenario, imports are assumed to be indirectly re-exported for net-exporting countries.

Figure 6 **A** shows the MPW generation for the direct re-export scenario in 2016. It becomes clear that areas with dense populations are most likely to have the highest MPW generation per year. However, the mismanaged waste fraction and GDP are also of influence as many higher-income countries with dense populations have lower levels of MPW generation (e.g. The Netherlands) than lower or middle-income countries such as India. Both countries have approximately the same population density (e.g. 411 and 428

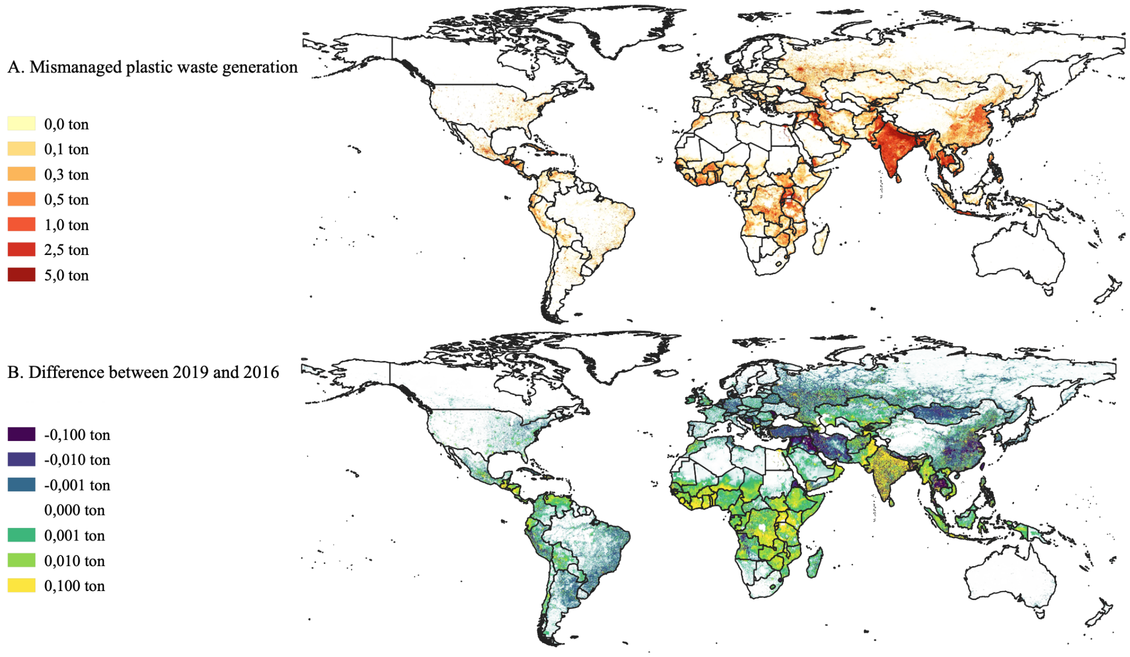

Figure 6. Mismanaged plastic waste generation for the direct re-exports scenario in 2016 (**A**), and the difference between this scenario in 2016 and 2019 (**B**). Both maps are a 30 arc second grid. The legend indicates the mass generation and difference in tons per year per raster cell.

citizens per square kilometer, respectively[31]), but whereas The Netherlands generates 1.46 kg MPW per capita per year, India generates 12.8 kg MPW per capita per year[19][16].

Figure 6 **B** shows the difference between the two scenarios in 2016 and 2019. Global MPW generation in 2016 and 2019 increased from between 61.6 and 62.5 million ton to between 64.1 and 65.2 million ton. This is an increase of approximately 4.1%, which is above the approximately 3.35% global population increase[25]. China shows both a decrease and increase in MPW generation. Since its population barely grew (0.88% [25]), the decrease near the coast indicates to be an effect of reduced imports[11]. Also, urbanization could explain the in-land decrease and increase near larger urban areas[32]. A relatively strong increase in MPW generation occurred in the Asia (other than China, Hong Kong SAR and Macao SAR) and in Sub-Saharan Africa. The increase in both regions could be explained by the population increase[25] and increased imports of plastic waste[16].

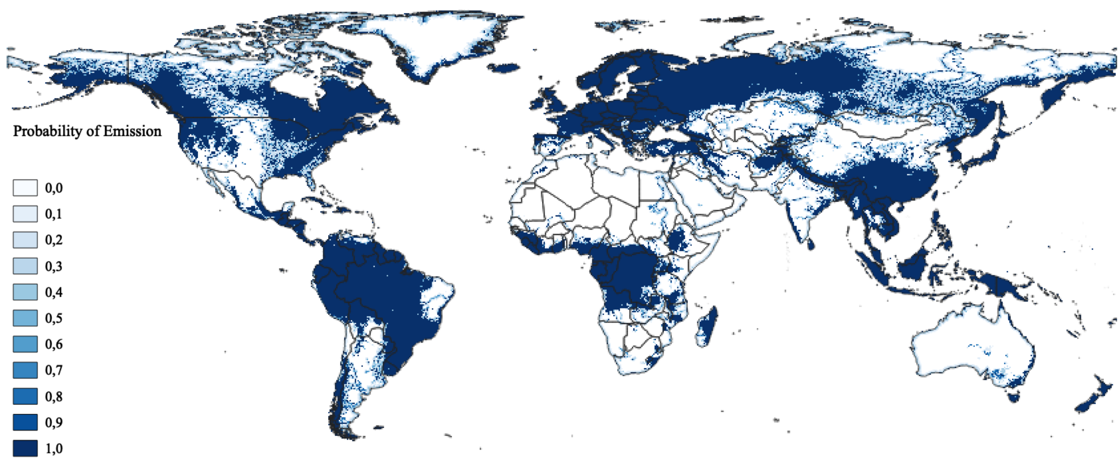

Figure 7. 30 arc second probability of emission map, where 1.0 is 100% chance of emission.

3.3 Probability of emission

The probability of emission map (figure 7) shows that areas close coastlines and river basins with relatively many perennial rivers and streams are most likely to emit mismanaged plastic waste. The probability of emission decreases when distance to an aquatic environment increases. Large regions in North and South America, Europe, Asia and Africa (near the Congo river basin) have a probability of emission of 100% as for the denseness of perennial rivers and streams in these in-land areas[15].

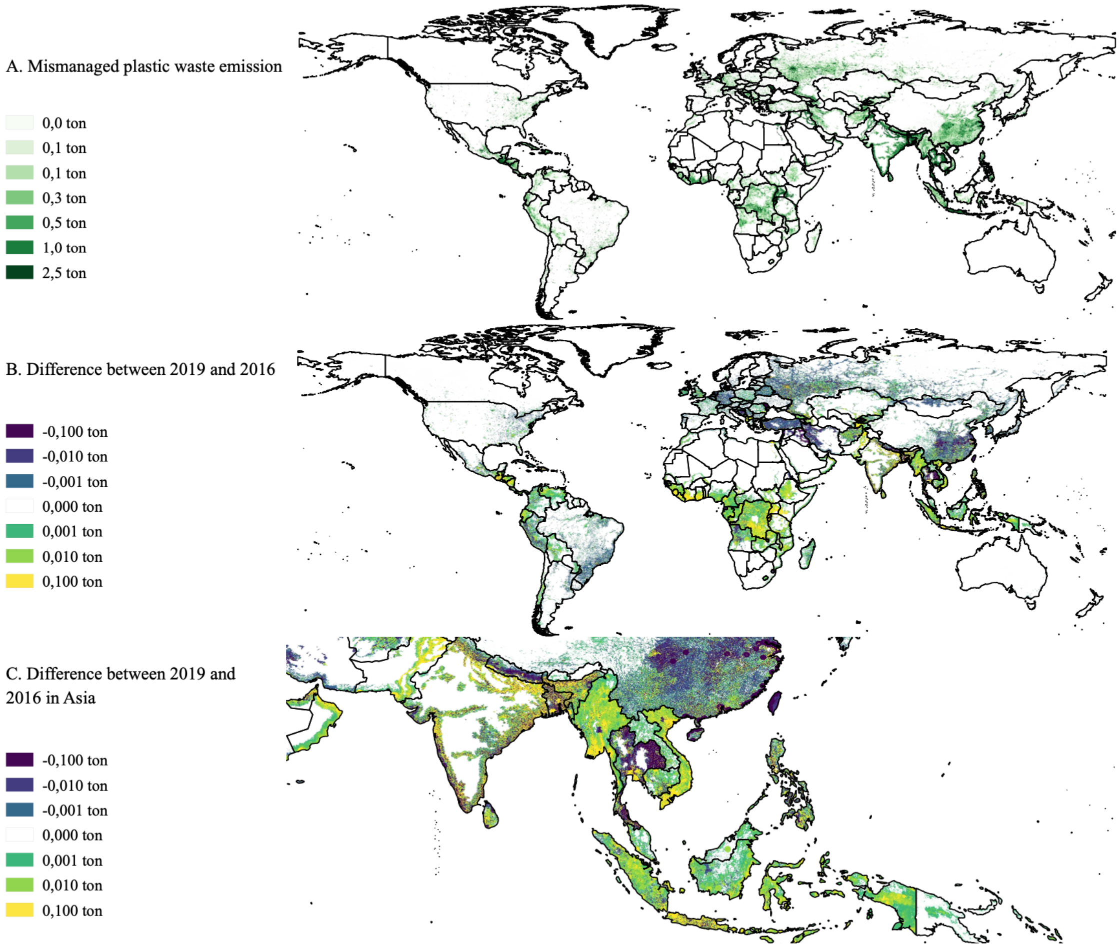

Figure 8. Mismanaged plastic waste emission for the direct re-exports scenario in 2016 (**A**), the difference between this scenario in 2019 and 2016 (**B**), and the same difference map enlarged for Asia (**C**). All maps are a 30 arc second grid.

3.4 Emission of mismanaged plastic waste

Figure 8 **A** shows the MPW emission for the direct re-export scenario in 2016 and a difference map between this scenario for 2016 and 2019 (find other maps in supplementary materials). Map **A** in figure 8 is a combination of figure 6 map **A** and figure 7. This becomes clear from the dark green areas in Asia where a high number mismanaged plastic waste is generated annually, and which is almost completely subject to a 100% probability of emission.

Whereas between 39.3 and 39.8 million ton mismanaged plastic waste was emitted into the aquatic environment (referred to as aquatic MPW emissions) in 2016, this number increased by 2019 to between 40.6 and 41.3 million ton. This is an increase of approximately 3.6%. Despite seeing the highest density of aquatic

MPW emission in Asia, the Russian Federation has on a country-level the highest aquatic MPW emission, with between 7,267 and 7,470 kilo tons. It emits 18% globally for both 2016 and 2019. The second and third largest aquatic MPW emitters in 2016 and 2019 were India (between 4,482 and 4,583 kilo tons) and China (between 2,706 and 3,165 kilo tons). The three largest emitters are responsible for 35% to 38% of global aquatic MPW emissions in 2016 and 2019. Whereas emissions of the Russian Federation and India grew by approximately 2.5%, China its emissions decreased by approximately 14.3%.

The difference maps in figure 8 **B** and **C** show where the emission into the aquatic environment changed between 2016 and 2019. As discussed before, it becomes clear that China is mostly experiencing a decrease, whereas other Asian countries are experiencing mostly an increase in MPW generation and emission. Where most in-land emissions into the aquatic environment differ on a more granular basis per cell, changes in emissions around ports are clearly visible from dark purple or yellow circles. China its total emissions decreased, partially due to reduced plastic waste imports after the China import ban[11], which confirms the dark purple circles around its coastlines and near major in-land rivers. Contrary, countries such as Malaysia, Vietnam and Indonesia imported up to 600% more plastic waste after the China import ban compared to before[16], which becomes clear from the yellow circles.

Plastic waste import emissions

The aquatic MPW emissions from ports contributed between 1.65% to 2.09%, and 1.16% to 1.61% to global aquatic MPW emissions in 2016 and 2019, respectively (figure 9). A decrease in 2019 can be explained from the 43.1% reduction in total plastic waste trade[16]. However, the MPW emission from ports decreased by approximately 23.5%. This can be explained by the increase in MPW from imports in other lower and middle-income countries than China (e.g. Turkey, Malaysia, Vietnam, and Indonesia (figure 4)), which have a higher mismanagement rate and a higher probability of emission near ports. Whereas China has a mean probability of emission of approximately 73%, these countries with increased imports have a mean probability of emission between 87% and 100%. Despite the decline in aquatic MPW emissions from ports, the 1.4 million ton increase in domestic produced aquatic MPW emissions cause the total aquatic MPW emissions to increase by approximately 3.6%.

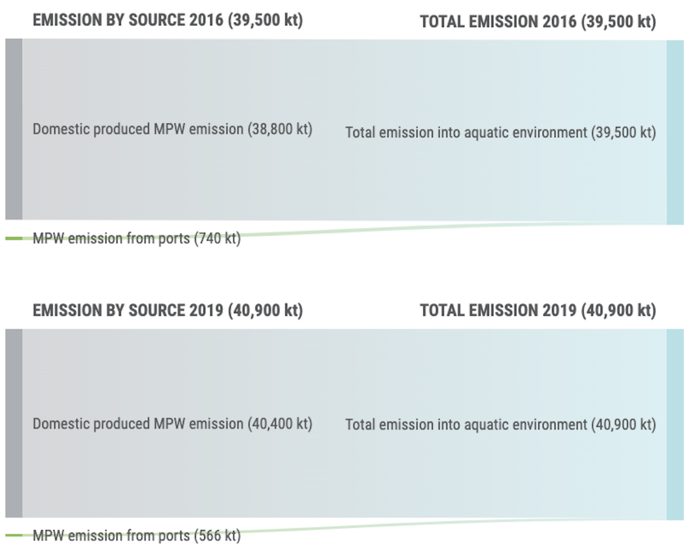

Figure 9. Sankey-diagram of the mean global mismanaged plastic waste leakage from ports and domestic produced MPW in 2016 and 2019, in kilo tons (kt). The Sankey-diagram was made with Metabolic B.V. its software.

Table 3. The ten countries with the largest MPW emissions from ports, and the share of total MPW emissions for 2016 and 2019, where *kt* is kilo tons.

Countries	2016 Mean port emission (kt)	2016 Share of total emission	2019 Mean port emission (kt)	2019 Share of total emission
China	461.3	14.6%	18.0	0.7%
India	126.6	2.8%	118.6	2.3%
Vietnam	42.6	10.0%	55.1	11.6%
Turkey	42.1	10.2%	172.5	32.1%
Russian Federation	13.1	0.1%	53.1	0.7%
Thailand	10.2	1.0%	29.8	2.6%
Indonesia	5.5	1.0%	19.1	1.7%
Pakistan	5.1	2.0%	19.1	3.3%
Myanmar	1.5	1.0%	16.3	4.3%
Philippines	1.2	0.4%	4.9	1.7%

Table 3 shows the MPW emission and its share of total emissions for the ten countries with largest aquatic port emissions. These ten countries were responsible for 88% to 98% of global aquatic port emissions in 2016 and 2019. Whereas China was responsible for 55% to 70% of global port emissions in 2016, it was responsible for approximately 3.2% of global port emissions in 2019. A reduction of more than 400 kilo tons of aquatic MPW emissions from Chinese ports, which accounts for 97% of the reduction in total aquatic MPW emissions from China between 2016 and 2019. Despite this substantial reduction from Chinese MPW import emissions, global import emissions were reduced by 174 kilo tons as a result of other countries that are importing more plastic waste since the China import ban. Turkey, the Russian Federation, Indonesia and Pakistan its aquatic port emissions grew by close to 300%, and Myanmar its aquatic port emissions grew by over 900% (table 3).

4. Sensitivity Analysis

The probability of emission is a distance-based function for each level 12 hydroBASIN[26] to the closest basin with a perennial river or stream segment, or coastline. A perennial river or stream has a long term minimal average discharge of 0.0 m^3s^{-1}, which is intermittent for less than one day per year[15]. A river or stream is considered 100% perennial if it has a 0% probability of intermittence. The binary flow intermittence class with a 50% probability threshold is used in this study as there is a rather small fraction of 100% perennial rivers and streams (e.g. 47 river segments out of 1.37 million in Asia). However, non-perennial rivers and streams are more common than perennial rivers and streams[15], which suggests that the binary flow intermittence class might not be the best indicator.

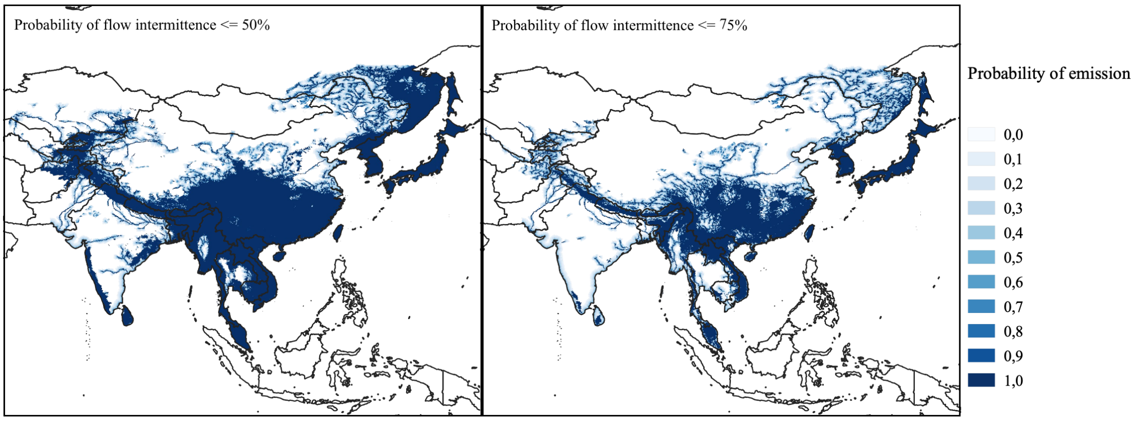

Figure 10. The probability of emission with a probability of flow intermittence lower than 50%, as used for the greater part of this study (left), and a flow intermittence lower than 25% (right).

A probability of emission map is created for Asia with a 25% probability of river segments being perennial (figure 10). The probabilities near the coast did not change. The figure shows a clear reduction of in-land areas with a 100% probability of emission as a result of a 56% reduction in perennial rivers and streams. This reduction results in a decrease in aquatic MPW emission by Asia of approximately 4,508 kilo ton, or 34%. Areas furthest from coasts and major river basins experienced the biggest relative change, with Mongolia, Cambodia and Kazakhstan all having their aquatic MPW emissions decreased by 71% to 81%. However, their total emissions accounted for 2% of total Asian emissions. India (-38%), Thailand (-51%) and China (-20%) experienced the biggest absolute change and accounted together for more than 70% of the total Asian aquatic MPW emissions. Figure 10 shows that India and Thailand its close to 100% emission regions (i.e. dark blue areas) vanish almost entirely with a reduced probability of intermittence.

5. Discussion

It becomes clear that the China import ban had a substantial effect on global plastic waste trade. Overall trade decreased by more than 40% compared to the baseline year, Chinese imports decreased by approximately 96%, and imports by other lower or middle-income countries increased up to 600%. The countries with the highest share of exports to China, Hong Kong SAR, and Macao SAR experienced the most significant decrease, and the largest importers and exporters remained the same, but with less quantity. This suggests that the China import ban affected the global plastic waste trade structure such that plastic waste is partially exported to other countries, with possibly less advanced treatment facilities. This part of the research did not include the effect of the China import ban on greenhouse gas emissions from plastic waste transport, which could be interesting for future research. No data was found regarding what ports are used for international plastic waste trade, nor the requirements for ships transporting plastic to dock in a port. The assumption is therefore made that all ports per country, despite the size, are evenly likely to import and export plastic waste. This is a limitation and could be improved in further research.

The scenario study is relevant to the mismanaged plastic waste generation as a net-exporting country should have enough domestic produced plastic waste to account for all the exports. There are nine countries that cannot provide enough plastic waste. This is possible as the UN Comtrade data and the What a Waste Database do not include stock. Except for Macao SAR and the Marshall Islands, the seven other countries have mismanaged waste fractions close to 100%, which means that almost no domestic produced plastic waste remains for export after it is inadequately managed. To account for this missing fraction in the mass balance, the domestic produced plastic waste is increased by exactly what is missing for exports. However, due to high mismanaged waste fractions, and therefore little remaining plastic waste for exports, domestic production is increased up to 480%. This could be considered a limitation of this study. Thus, either stock is not accounted for, or the mismanaged waste fraction should be lower. The latter for these countries was not filled by the kNN-algorithm, but was provided by the What a Waste database.

The highest mismanaged plastic waste generation levels are in areas with a high population density and high mismanaged waste fractions, which mainly consists of lower or middle-income countries in Asia or Africa. There is a clear shift in MPW generation between 2016 and 2019 in Asian countries. China has a overall reduction and other Asian countries such as Malaysia and Indonesia experience an increase. The difference between these two years is the result of changing populations and the changes in global plastic waste trade. In order to study the impact of plastic waste trade, and as for limited availability or strongly diverging data on waste fractions in 2016, this study assumes the municipal solid waste generation, plastic waste fraction and mismanaged waste fraction to be the same in 2016 and 2019.

The probability of emission into the aquatic environment is based on earlier research, which defined aquatic ecosystems as a surface area of at least 10,000 km^2 with flow accumulation[27]. Since there are rather few surface areas with at least 10,000 km^2 and flow accumulation besides the marine environment, not many lakes and major rivers were included where plastic accumulation could occur as well. Therefore a distinction in definition is made with the purpose to also include aquatic areas where plastic waste could accumulate. Besides the marine environment and lakes, perennial rivers and streams are included in this study. By including these rivers and streams, in-land generated MPW could potentially also end up in aquatic environments, despite most of these rivers and streams not having a surface area greater than 10,000 km^2.

The probability of emission is the highest near coast lines or perennial rivers and streams. For the greater part of this study, a binary flow intermittence with a 50% probability threshold was used. However, as non-perennial rivers and streams are considered more common, this threshold might not reflect reality. Changing the probability of intermittence threshold to 75% showed a 34% reduction of mismanaged plastic waste emissions in Asia. It should thus be noted that defining a probability of emission function based on perennial rivers and streams comes with great uncertainty.

Total mismanaged plastic waste emissions into the aquatic environment increased from between 39.3 and 39.8 to 40.6 and 41.3, or approximately 3.6% between 2016 and 2019. Global and some national MPW emission into the aquatic environment statistics are substantially higher than what other studies have reported. This can be explained by the different modelling approaches and the different definition of the aquatic environment as most other studies focus solely on the marine environment. Earlier research concluded that 98.5% of generated MPW remains trapped on terrestrial environments and does not reach the marine environment[10]. Reducing the total MPW generation of this study by this percentages results in MPW emissions into the marine environment ranging between 0.93 and 0.99 million ton, which matches the results by [10].

6. Conclusion

This study presents the global mismanaged plastic waste emissions into the aquatic environment before and after the China import ban on a 30 arc second resolution (approximately 1 square kilometer). The China import ban affects global leakage rates of mismanaged plastic waste into the aquatic environment in the following ways. Firstly, global traded plastic waste and its related MPW emission into the aquatic environment decreased by more than 40% and 23%, respectively. Secondly, other lower or middle-income countries than China, Hong Kong SAR and Macao SAR, experienced a steep increase of mismanaged plastic waste emissions into the aquatic environment after the China import ban. These increases were caused by increased plastic waste imports. This indicates that Chinese plastic waste imports shifted to other lower or middle-income countries. Most of these countries have a higher probability of emission, which explains a less substantial decrease in aquatic MPW emissions from ports, than the decrease in total traded mass.

Despite countries other than China facing steep increases, global trade and its related emissions into the aquatic environment became significantly less. The hypothesis can therefore be rejected.

Although global mismanaged plastic waste emissions into the aquatic environment increased by approximately 3.6% between 2016 and 2019, this could have been higher if the China import ban was not issued and trade developed in a similar manner.

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