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Original Article

물질흐름분석을 활용한 전세계 플라스틱 해양쓰레기의 유입량과 현존량 추정: 예비적 접근

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Estimating the Global Inflow and Stock of Plastic Marine Debris Using Material Flow Analysis: a Preliminary Approach

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요 약

전세계 플라스틱 해양쓰레기의 유입량과 현존량을 추정하였다. 한국에서 플라스틱 해양쓰레기의 연간 유입량(72,956톤)은 플라스틱의 연간 소비량(5.2백만톤)의 1.4%로 추정되었다. 유출량이 0이라는 가정과 함께, 이 1.4% 유입률을 1950년부터 2013년까지 전세계 플라스틱 생산량에 적용함으로써, 2013년 전세계 연간 플라스틱 해양쓰레기 유입량은 4.2백만톤이며, 2013년말 현재 플라스틱 해양쓰레기 현존량은 86백만톤으로 추정되었다. 또한 로지스틱 모델에 따라, 석유생산량의 4%가 플라스틱으로 생산될 때 플라스틱 해양쓰레기의 최종 현존량은 199백만톤이 될 것으로 추정되었다. 유입량과 현존량은 전혀 다른 측정단위이기 때문에, 유입 저감 정책의 효과성을 평가할 수 있는 개선된 지표가 필요하다. 또한, 플라스틱 해양쓰레기 오염은 거의 회복불가능하기 때문에, 이를 예방하는 대책의 가치는 훨씬 더 높게 평가되어야 하며, 사전주의의 원칙에 따라 더 강력한 예방 대책이 시행되어야 한다. 본 연구는 제한적인 정보에 근거한 예비 연구에 해당하므로 플라스틱 해양쓰레기의 유입량과 현존량의 경향을 규명하기 위한 추가 연구가 필요하다.

Abstract – We estimated the global inflow and stock of plastic marine debris. In South Korea, we estimated that the annual inflow of plastic marine debris (72,956 tons) was about 1.4% of annual plastics consumption (5.2 million tons) in 2012. By applying this 1.4% ratio to global plastics production from 1950 to 2013, we estimated that 4.2 million tons of plastic debris entered the ocean in 2013 and that there is a stock of 86 million tons of plastic marine debris as of the end of 2013, assuming zero outflow. In addition, with a logistic model, if 4% of petroleum is turned into plastics, the final stock of plastic marine debris shall be 199 million tons at the end. As the inflow and the stock are different units of measurement, better indicators to assess the effectiveness of inflow-reducing policies are needed. And, as the pollution from plastic marine debris is almost irreversible, countermeasures to prevent it should be valued more, and stronger preventive measures should be taken under the precautionary principle. As this is a preliminary study based on limited information, further research is needed to clarify the tendency of inflow and stock of plastic marine debris.

Keywords: Plastic marine debris(플라스틱 해양쓰레기), Inflow(유입량), Stock(현존량), Material flow analysis (물질흐름분석), Policy indicators(정책 지표)

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1. Introduction

How much plastic marine debris is there in the ocean? How much is entering the ocean every year? These questions are increasingly important (UNGA [2005]; Ryan *et al*. [2009]) as scientific evidence mounts that marine debris, and plastic marine debris in particular, is harmful to both human health and marine ecology (Rochman *et al*. [2013]). For example, it is estimated that plastic marine debris costs approximately US$13 billion per year in environmental damage to marine ecosystems (UNEP [2014]). A problem can be managed only when it is adequately understood, and information on the amount of plastic marine debris is a vital step toward finding a solution (UNEP [2014]).

Previous efforts to answer these questions can be divided into two groups: those addressing the 'inflow,' and those addressing the 'stock' of marine debris. A 'flow' is measured for a certain period of time, while a 'stock' is measured at a specific moment in time. Regarding inflow, NAS [1975] estimated that 6,360,000 tons of marine debris enters the ocean every year from ocean-based activities, while Cantin *et al*. [1990] estimated that 337,306 tons enter US waters. Kataoka *et al*. [2013] estimated that at least 2,115 m^3 of grass flows into Tokyo Bay, Japan annually via rivers. Jang *et al*. [2014A] estimated that 91,195 tons of marine debris enters the ocean from activities on land and at sea. The highest estimates suggest inflow as high as 7 billion tons per year (GBRMPA [2006]), though these may be overestimates (Cheshire *et al*.[2009]).

Likewise, several recent studies have examined the stock of marine debris. Cozar *et al*. [2014] estimated that the global stock of plastic debris in surface waters of the open ocean ranges from 6,600 to 35,200 tons, based on samples collected from 442 sites in 2010. Similarly, Eriksen [2014] estimated that there are 269,000 tons of plastic in global ocean surface waters based on 26 expeditions over 6 years. Jang *et al*. [2014A] estimated that 152,241 tons of marine debris could be found on the coast, sea floor, sea surface, and water column of the South Korean sea.

However, these studies provide only a very limited picture of global pollution from plastic marine debris. The NAS [1975] estimate is outdated and limited to debris from activities on the ocean, only 0.7% of which is plastic (Lebreton *et al*. [2012]); instead, the estimate includes other materials such as metals, and even organics such as food waste. The estimate from Cantin *et al*. [1990] is also limited to debris from activities in US waters. Most of the debris described by Kataoka *et al*. [2013] is grass, not anthropogenic in origin. Likewise, the findings of Jang *et al*. [2014A] are limited to South Korean waters, and the two remaining estimates of debris stock (Cozar *et al*. [2014]; Eriksen *et al*. [2014]) are limited to surface debris, not including debris on the coast or sea floor.

Here, we estimate the global inflow and stock of plastic marine debris based on rates of plastic consumption. First, we estimate the inflow ratio (plastic marine debris inflow / plastic consumption) from plastic material flow analysis in South Korea. Material flow analysis is a method of analyzing the amount of materials in a certain system, and is proper for polluting materials (OECD [2008]). Second, we apply this inflow ratio to data on the global production of plastic (1950-2013) to estimate the global inflow and stock of plastic marine debris. Third, we speculate on the inflow and stock of plastic marine debris after 2013, under the assumption that a constant proportion of petroleum is made into plastics. Finally, we discuss conceptual differences between plastic marine debris inflow and stock.

2. Methods

2.1 Inflow ratio of plastic marine debris

We defined the inflow ratio of plastic marine debris as follows:

$$\text{Inflow ratio of plastic marine debris} = \frac{\text{Annual plastic marine debris inflow to the ocean}}{\text{Annual plastic consumption}} \quad (1)$$

Here, we applied the inflow ratio for South Korea globally. The annual plastic marine debris inflow for South Korea was derived from Jang *et al*. [2014A], which is a national-level synthesis of previous studies.

Annual plastic consumption in South Korea was estimated by a material flow analysis (OECD [2008]) of plastics. Material flow analysis (MFA) is a systematic assessment of the flows and stocks of materials within a system defined in space and time (Brunner [2004]). In this case, various data on plastics production and consumption in South Korea were used. Under South Korean law, any large business that manufactures or imports plastic products (excluding packaging materials) for domestic consumption must pay a tax for the waste. Moreover, any business that manufactures or imports plastic packaging materials must recycle a certain proportion (about 80%) (Act on the Promotion of Saving and Recycling of Resources [2014]) under Extended Producers Responsibility regulations (OECD [2001]). Thus, the government collects various data related to plastics consumption.

To simplify the calculation, we assumed that the lifetime of all plastic products is less than one year. That is, the amounts of plastic production, consumption, and waste in a given year were assumed to be the same, although some products are in use for longer periods. For example, the percentage of packaging material in the usage of plastic is 37% in the United Kingdom (Hopewell *et al*. [2009]) and 39% in the Europe (Plastics Europe [2013]). However, even when the lifetime of products are longer than one year, it does not affect the final discharge amount of debris, as there shall be only time gap.

For the material flow analysis, the study site was defined as the territory and sea of South Korea, and the time as the calendar year 2013, except where 2013 data were not available, in which case 2012 data were used.

2.2 Global inflow and stock of plastic marine debris (1950-2013)

Next, the inflow ratio was applied to data on global plastic production estimated by Plastics Europe (2011, 2012, 2013, and 2014) to estimate the global inflow and stock of plastic marine debris from 1950 to 2013. For this purpose, we assumed that plastic marine debris outflow, such as beach cleanup efforts or plastic biodegradation, does not occur. That is, although there are in fact some outflows, we assumed there were none for simplicity, an assumption we address below. We also assumed that the inflow ratio is the same irrespective of nation or year. Under these assumptions, the accumulation of inflow from 1950 to a certain year becomes the stock at the end of that year (Eq. 2). We discuss the reliability of these assumptions in the discussion section below.

Stock of plastic marine debris at the end of a certain year = Accumulated sum of the inflow of plactic marine debris from 1950 to that year (2)

2.3 Speculating on the plastic marine debris level after 2013

We speculatively estimated the potential level of plastic marine debris after 2013, assuming that the ratio of plastic marine debris inflow to plastic production, and the ratio of plastic production to petroleum production, are both constant over time. About 4% of total petroleum is made into plastics (Hopewell *et al*. [2009]; British Plastics Federation [2012]), and a further 4% is used for this production (Thompson *et al*. [2011]). Although plastics can be produced from other sources such as coal and gas, we analyzed plastics made from petroleum only, and used speculative petroleum production data from Gallagher [2011].

If 4% of petroleum is made into plastics, and the same proportion of plastics becomes marine debris each year, then the plastic marine debris will follow the same pattern as petroleum production—a logistic curve (Hubbert [1956]). The well-known logistic function (Verhulst [1838]) is given by Eq. (3):

$$S(y) = K/\left(1+\left(\frac{k}{s_o}-1\right)e^{-ry}\right) \tag{3}$$

where $S(y)$ is the stock of plastic marine debris in tons as a function of time (year); K is the final stock of plastic marine debris (carrying capacity); S_0 is the initial stock; r is the growth rate, which is the same as that for petroleum production; and y is the year (time).

As we assumed that plastic marine debris follows the same pattern as petroleum production, r is the same as for petroleum, and K is calculated as a portion (4% × inflow ratio) of the final cumulative petroleum production.

As a special feature of the logistic curve, maximum inflow occurs when the stock is half of the final stock, K (Gallagher[2011]). Thus, the inflow curve is shaped like a bell or peak, of which the center is the maximum.

3. Results

3.1 Inflow ratio of plastic marine debris into the ocean

To determine the inflow ratio of plastic marine debris into the ocean, we conducted a material flow analysis of plastics and plastic marine debris (Fig. 1). In 2012, 13,355,000 tons ('B' in Fig. 1) of plastic pellets (a precursor to most plastic products) were produced in South Korea; 7,487,000 tons ('D') were exported, an additional 465,000 tons ('E') were imported, and 5,868,000 tons ('C') were used to produce 6,333,000 tons ('F') of plastic products (Korea Plastic Manufacturing Cooperatives, 2014). In 2013, 5,176,358 tons ('J') of plastic products were consumed, comprising 4,036,358 tons ('G') of products manufactured domestically and 1,140,000 tons ('I') imported (Korea Packaging Recycling Cooperative, 2014; Korea Ministry of Environment, 2014). After consumption, 4,500,351 tons ('K') were treated at waste plants (Korea Environment Corporation, 2012).

The annual inflow of marine debris in 2012 was estimated at 72,956 tons ('R' in Fig. 1). This was calculated by multiplying the total annual inflow (91,195 tons in South Korea; Jang *et al*. [2014A]) by the 80% ratio of plastics in marine debris (Derraik [2002]), and is the sum of the inflows from activities in the sea ('M' = 58,370 tons × 80% = 46,696) and on land ('N' = 32,825 tons × 80% = 26,260). Thus, the plastic marine debris inflow ratio is approximately 1.4% (72,956 / 5,176,358 = 1.4%) (Table 1).

3.2 Global inflow and stock of plastic marine debris

To estimate the stock of plastic marine debris, we applied the

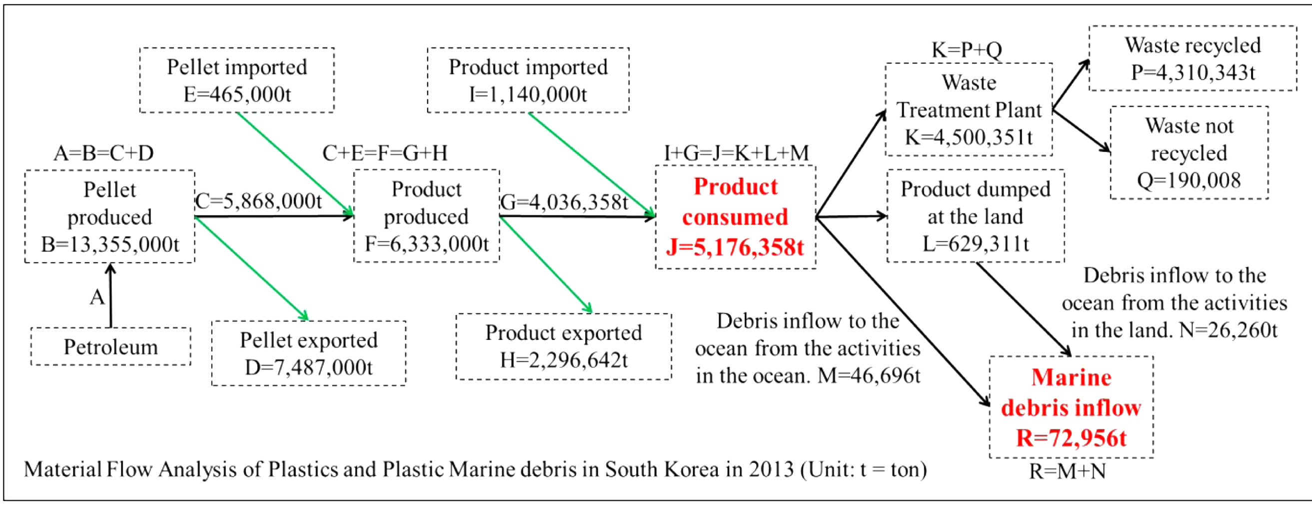

Fig. 1. Material flow analysis of plastics and plastic marine debris in South Korea in 2013. (Drawn by this research based on data from Korea Plastic Manufacturing Cooperatives (2014), Korea Packaging Recycling Cooperative (2014), Korea Ministry of Environment (2014), Korea Environment Corporation (2012), and Jang *et al*. (2014A)).

Table 1. Plastic marine debris inflow ratio for South Korea (2013)

Items	Amount (weight, ton)	References
Annual marine debris inflow	91,195	Jang *et al.* [2014A]
Ratio of plastics in marine debris	80%	Derraik [2002]; #1
Annual plastic marine debris inflow	72,956	91,195×80%=72,956
Annual plastic consumption ('J' in Fig. 1.)	5,176,358	MOK [2014]; KPRC [2014]
Plastic marine debris inflow ratio	1.4%	72,956 / 5,176,358 = 1.4%

#1. Though Derraik [2002] has shown 60 to 80% are plastic, 80% was applied for simplification.

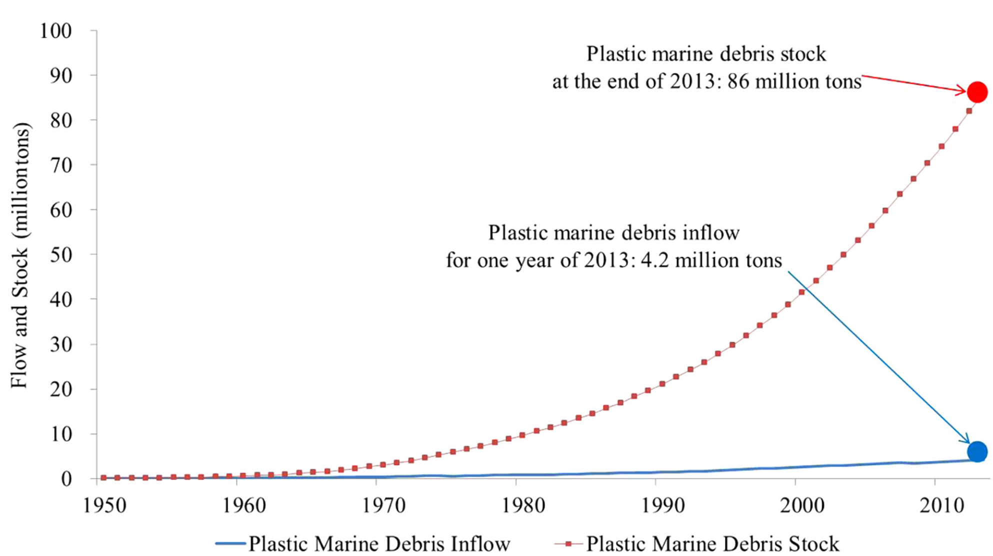

Fig. 2. Plastic marine debris inflow and stock worldwide, under the assumption that 1.4% of plastic production enters the ocean. As the stock is the accumulation of the inflow, the stock is around 20-fold larger than the yearly inflow as of 2013.

1.4% ratio (Table 1) to data on global plastic production provided by Plastics Europe (2011, 2012, 2013, 2014). However, as only general production trends in plastic production are publically available in these documents, we obtained specific data for each year via personal communication with Plastics Europe. Though plastics were produced before 1950, this was dismissed for simplification. Annual plastics production information is attached as an appendix below.

Using these data, we calculated the global plastic marine debris stock at the end of 2013 as 86 million tons and the plastic marine debris inflow for the single year 2013 as 4.2 million tons (Fig. 2). As the stock is the accumulation of the inflow, the stock is around 20 times larger than the yearly inflow as of 2013.

3.3 Speculation on plastic marine debris levels after 2013

According to Gallagher [2011], the total accumulated production (carrying capacity) of petroleum will ultimately be 2.24 trillion barrels, and peak oil occurred in 2009. Next, we apply the 4% ratio of petroleum turned into plastics and the 1.4% ratio of plastic marine debris inflow. As 1 barrel equals 0.1589 tons, the final total plastic marine debris stock (K in the Eq. 3) will be about 199 million tons (= 2.24 trillion barrels × 0.1589 × 0.04 × 0.014), and the maximum inflow of plastic marine debris will be 2.9 million tons (30.2 billion tons × 0.1589 × 0.04 × 0.014) in 2009 (Fig. 3). As the maximum inflow occurs when the stock is half of K, the stock in 2009 is 99 million tons (half of 199 m tons). Although these estimates of petroleum production may change if new petroleum resources are found, this figure gives a glimpse into the potential plastic marine debris volume of the future.

The speculative estimate of plastic marine debris inflow and stock based on petroleum production (Fig. 3) differs from the estimate based on plastic production (Fig. 2). For example, for the year 2009, the inflow is similar but not the same (3.5 million tons ≠ 2.9 million tons), and the stock is likewise (70 million tons ≠ 99 million tons). Such differences are brought about by different input factors, such as growth rates, initial stock, and carrying capacity. In particular, for the speculative estimate after 2013, we assumed that only petroleum, and no other material, was used to make plastics.

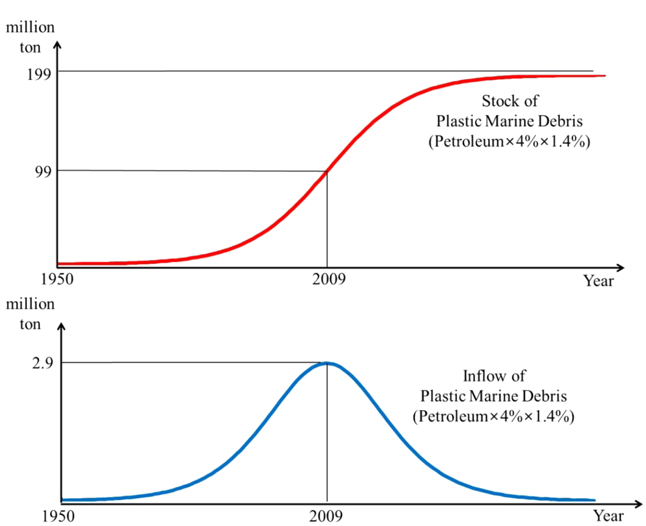

Fig. 3. Speculation on plastic marine debris stock and inflow after 1950 with the assumption that 4% of petroleum is turned into plastics and that 1.4% of plastics become marine debris.

4. Discussion

4.1 Review of assumptions

In this study, we assumed that the inflow ratio (annual plastic marine debris inflow per unit of plastic consumption) was the same for all countries and years from 1950 to 2013. But the inflow ratio can change. For example, Liu *et al*. [2013] found that strong recycling policies regarding plastic bags and bottles decreased these types of debris on beaches in Taiwan vs. the USA. We can generally assume that the inflow ratio will decrease as waste management improves. Although we assumed that the inflow ratio was the same for all countries and years, further studies are needed to determine the inflow ratios for specific countries and years.

We further assumed that plastic is not degraded in the ocean. The final stage of degradation is called mineralization, wherein carbon in polymers is converted into CO_2 (and ultimately incorporated into biomass), and there are some polymer types, such as aliphatic polyesters, that progress to this stage (Andrady [2011]). There are several methods of measuring polymer degradation, including molecular weight loss (Shah *et al*. [2008]). For example, Kim *et al*. [2006] found that polybutylene succinate (PBS) lost about 13% of its molecular weight while high-density polyethylene (HDPE) lost almost nothing when they were kept on experimental compost soil for 80 days. Thus, our assumption of no plastic degradation is not always true.

Although plastics might degrade in the marine environment, we can assume that this occurs very slowly. For example, Lambert *et al*. [2013] found that many nano-sized plastic particles are produced when the molecular weight of the plastic is lost. That is, more harmful pollutants are made when the original plastics are seemingly degraded, if they are not completely mineralized. And, as sunlight and oxygen, important factors in degradation, are limited in the marine environment, degradation is likely much slower in the ocean than on land (Andrady [2011]).

The degradation speed of plastics is unknown, especially in the ocean. If we suppose that plastics degrade in 600 years, for example, then the stock of plastic marine debris will lose 1/600 of its weight each year. In this case, the plastic marine debris stock in the year 2013 would be calculated as follows:

Plastic marine debris stock in the year 2013 (with 600 years of degradation)

$= \sum$ Inflow of plastic marine debris each year × (1 - (2013 - year) / 600)) = 84 million tons

Here, 84 million tons is about 98% of the 86 million tons we originally estimated. Thus, the assumption of no biodegradation does not significantly affect the result.

We also assumed that plastic marine debris collection is zero. Although a certain amount of plastic debris is collected around the world, the amount is insufficient to significantly influence the result. For example, only 570 tons of debris was removed for the 10 years from 1997 to 2006 in the USA (NOAA [2008]). Globally, 52,617 tons of debris was removed by millions of participants in the International Coastal Cleanup campaigns in the 21 years from 1986 to 2006 (NOAA [2008]).

For the speculative estimate after 2013, we used the peak oil estimate from Gallagher [2011]. Although there are fierce debates on the extent of petroleum reserves and the timing of peak oil (Chapman [2014]), this is not the focus of our study. Regardless of the extent of petroleum resources, it appears certain that the stock of plastic marine debris will hardly decline even if the production of plastics decreases in the future.

4.2 Comparison with previous estimates

In this study, the inflow ratio (annual plastic marine debris inflow / annual plastic consumption) was estimated at 1.4% (72,956 ton / 5,176,358 tons = 1.4%) in South Korea and then extrapolated worldwide. However, both debris inflow and plastic consumption may be underestimated. For example, to estimate marine debris inflow, we used data from the Han River in 2000 (Incheon City [2001]) as the inflow from land sources. That study used a 5-cm mesh net to collect debris from the river and, consequently, debris smaller than 5 cm, such as micro-beads (Fendall and Sewell [2009]), is not included in the inflow estimate. Plastic consumption was also underestimated because small businesses are not taxed for waste and are exempted from reporting the manufacture or importation of plastic (Korea Ministry of the Environment [2014]). Thus, it is unclear whether 1.4% is an over- or under-estimate.

Thompson [2006] suggested that upto 10% of plastics enter the ocean (Cole *et al*. [2011]). If 1.4% changes to 10%, then the inflow in 2013 would be 30 million tons and the stock at the end of 2013 615 million tons, based on our estimates (see Appendix). As there is no scientific basis on the 10% assumption of Thompson [2006], it is unclear if 10% is relatively large or small. Again, more work must be done to estimate the inflow ratio. In this respect, a recent attempt to estimate plastic debris inflow from the land on a per-country basis (Jambeck *et al*. [2015]) is highly valuable. The estimate of plastic marine debris inflow from the land in 2010 in South Korea (33,747 tons) by Jambeck *et al*. [2015] is not much different from our own estimate (26,260 tons). However, because debris inflow from activities in the ocean can exceed that from activities on land in some countries (Jang *et al*. [2014B]), it is important to also consider debris inflow from activities in the ocean.

Our estimate of plastic marine debris inflow from activities in the ocean is much smaller than that of NAS [1975], which estimated it at 6,360,000 tons in 1975. This is markedly larger than our estimates of 560,000 tons of inflow in 1975 and 4.2 million tons in 2013 (see Appendix). Such a difference can be explained in part by the fact that the NAS [1975] estimate occurred before MARPOL 73/78 (IMO [1997]) which prohibited pollution from ships, including plastics and other materials such as metal (cargo boxes) and food waste. Notably, 88% (5,600,000 / 6,360,000 tons) of the garbage from NAS [1975] was lost cargo from merchant shipping, and such losses have been dramatically reduced with the development of shipping technology. Moreover, only 0.7% (44,520 tons) of the 6,360,000 tons of NAS [1975] was plastic (Lebreton *et al*. [2012]).

The two previous estimates of stock, 6,600-35,200 tons (Cozar *et al*. [2014]) and 269,000 tons (Eriksen [2014]), are much smaller than our estimate of 86 million tons. This difference can be explained in part by the fact that a large portion of plastic marine debris accumulates on the sea bottom. For example, Jang *et al.* [2014A] estimated that 90% of marine debris stock (152,241 tons) is on the sea floor, 8% on the beaches, and only 2% in the water column and on the sea surface in South Korean waters. If we take 2% of our 86,219,000-ton stock estimate, we obtain 1,724,380 tons as an estimate of plastic marine debris on the sea surface and in the water column. This is still larger than 269,000 tons; however, the estimates of Eriksen [2014] and Cozar *et al*. [2014] consider only plastic marine debris on the surface and would presumably be higher if they included debris in the water column.

Regarding plastic marine debris on the sea floor, we must remember that formerly floating debris can eventually become submerged. Although some plastics are lighter than water, these light plastics can gain weight and accumulate on the sea floor for various reasons, such as plankton fouling (Andrady [2011]). Likely because of this, there are reports of plastic marine debris on the sea floor as deep as 1000 m (Debrot *et al.* [2014]; Eryasa *et al*. [2014]; and Galgani *et al.*, [2000]). Furthermore, fishing nets and ropes made of polypropylene and polyethylene (Jang *et al*. [2014B]) are the main components of marine debris collected from the sea bottom in South Korea (MLTM [2009]). Again, Cozar *et al*. [2014] and Eriksen [2014] considered only the water surface, and did not consider plastic marine debris in the water column.

4.3 The value of preventive measures against irreversible pollution and adequate indicators

If biodegradation of plastic debris in the ocean is close to zero, we might say that pollution from plastic marine debris is irreversible, much as the discharge of non-degradable pesticides is irreversible (Arrow and Fisher [1974]). If a certain type of pollution is irreversible, countermeasures to prevent it should be valued more, and stronger preventive measures should be taken under the Precautionary Principle (Gollier *et al*. [2000]). Moreover, when pollution is irreversible, reducing the stock is almost infinitely costly. Thus, we must develop more policies to reduce the inflow of plastic marine debris into the ocean.

However, the effectiveness of policies to reduce the inflow of plastic marine debris should be measurable and evidence-based (Sanderson[2002]). If certain policies are more effective in reducing plastic debris inflow, they should be more supported financially. To that end, the conceptual difference between inflow and stock should be clarified when developing policy indicators. In other words, we need to understand that current flow-reducing policy has very little effect on the marine debris stock. According to our estimate, for example, there is a stock of 86 million tons of plastic marine debris as of the end of 2013, yet only 4.2 million tons entered the ocean in 2013. Thus, even if marine debris inflow were completely eliminated in 2014, the stock at the end of 2014 would still be 86 million tons. Clearly, the effectiveness of policies to reduce inflow can hardly be measured by indicators based on marine debris stock.

As the effects of policy intervention differ according to the type of policy instrument used, the indicators should also differ (Table 2). For reducing debris inflow, the main policy indicator should be the amount of debris entering the ocean in a given period. For example, we might ask fishermen how much litter they produced during the past year. For reducing debris stock, the policy indicator should be the amount of debris found in the ocean. For example, we might measure the amount of marine debris on beaches at a certain point in time. The various types of policy strategies to cope with marine debris are listed on 'The Honolulu Strategy: A Global Framework for Prevention and Management of Marine Debris' (NOAA and UNEP [2011]. Unfortunately, there are few studies on the inflow of plastic marine debris, while many studies focus on the abundance—the stock—of marine debris in the ocean (Ryan *et al*. [2009]; Cheshire *et al*. [2009]; Cole *et al*. [2011]).

4.4 Future studies needed

Our study has many limitations. Many of the parameters used generally in this study are derived from the specific case of South Korea. Thus, more research is needed. First, plastic consumption should be investigated in more detail for specific countries. UNEP [2014] also emphasized that any problems 'can be managed when measured.' However, while UNEP [2014] is calling for participation from the business sector in measuring plastics, government should play the central role in this regard, as government policy impacts the management of plastic consumption and pollution. Material flow analysis will be a useful approach, of which Mutha *et al*. [2006] present a good example from India.

Second, estimating plastic marine debris inflow at the national level is vital but challenging. Jang *et al*. [2014A] reviewed several previous studies for this purpose in South Korea. These included (1) measuring debris inflow from rivers by capturing debris with nets across the Han River (Incheon City [2001]); (2) measuring debris inflow from rivers during a flood event (Geoje City [2013]); (3) measuring lost fishing gear and general garbage produced by ships via interviews with fishermen (MLTM [2009]); and (4) measuring lost aquaculture buoys via interviews with fishermen. These data were combined with governmental statistics to estimate the marine debris inflow. Though the accuracy of these types of measurement may be questioned, they appear to be the best of the methods currently available; clearly, better methods are needed. In particular, dumping, which determines debris inflow, is a human activity, and might be measured using social scientific methods.

Third, when estimating the stock of plastic marine debris,

Table 2. Examples of policy instruments and indicators for reducing marine debris flow and stock

Classification	Policy instruments	Policy indicators
Reducing marine debris inflow	(1) Collecting debris in rivers with booms. (2) Changing aquaculture practices. (3) Increasing the legally required ratio of recycling certain products via Extended Producers Responsibility.	(1) Amount of debris collected in a given period. (2) Fishermen's responses to the question of how much litter they produced in a given period. (3) Actual recycling ratio for the products.
Reducing marine debris stock	(1) Collecting from beaches. (2) Collecting from the seabed. (3) Collecting from the water surface and column.	(1) Amount of marine debris on beaches at a given point in time. (2) Amount of marine debris on the seabed at a given point in time. (3) Amount of marine debris on the water surface and in the column at a given point in time.

debris travel must be considered. For example, debris on beaches moves between the beach and sea many times each day (Kako *et al*. [2010]). Thus, care should be taken when estimating debris stock on beaches based on observations on beaches alone, because a beach is part of the sea. Estimating the stock on the sea surface might have the same challenges. As floating plastic debris moves through the water column via the process of plankton fouling (Andrady [2011]) and the water surface is part of the ocean, we should be careful when interpreting the abundance of floating plastic debris. Monitoring the abundance of plastic debris on the sea floor is also limited by technology and financial cost as huge sample sizes are required to overcome the very large spatial heterogeneity in plastic litter (Ryan *et al*. [2009]).

5. Conclusion

In this study, we estimated global plastic marine debris inflow and stock by applying material flow analysis of plastic marine debris in South Korea to global plastic production. We estimated that there is 86 million tons of plastic marine debris stock as of the end of 2013, 20-fold greater than the annual inflow (4.2 million tons for 2013). Thus, even if we reduce further inflow to zero, the stock will still be considered. Consequently, the effectiveness of inflow-reducing policies cannot be measured using indicators showing changes in the stock. As pollution from plastic marine debris is irreversible, the value of reducing debris inflow is much greater than for reversible pollution. Therefore, we must develop more methods of reducing inflow. As policies are more supported if their effectiveness is clear, better indicators are needed to show changes in inflow. To this end, we must pay careful attention to the conceptual difference between inflow and stock.

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Appendix. Calculation of inflow and stock of global plastic marine debris under the assumption that 1.4% of plastics enter the ocean and none is collected or biodegraded

Year	Plastics production (a)	Plastic marine debris inflow (b = a×1.4%)	Plastic marine debris stock (c = accumulation of 'b')	Year	Plastics production (a)	Plastic marine debris inflow (b = a×1.4%)	Plastic marine debris stock (c = accumulation of 'b')
1950	1,700,000	23,800	23,800	1982	63,000,000	882,000	11,403,000
1951	2,000,000	28,000	51,800	1983	69,000,000	966,000	12,369,000
1952	1,900,000	26,600	78,400	1984	74,000,000	1,036,000	13,405,000
1953	2,400,000	33,600	112,000	1985	78,000,000	1,092,000	14,497,000
1954	2,700,000	37,800	149,800	1986	83,000,000	1,162,000	15,659,000
1955	3,500,000	49,000	198,800	1987	90,000,000	1,260,000	16,919,000
1956	4,000,000	56,000	254,800	1988	96,000,000	1,344,000	18,263,000
1957	4,600,000	64,400	319,200	1989	99,000,000	1,386,000	19,649,000
1958	4,900,000	68,600	387,800	1990	105,000,000	1,470,000	21,119,000
1959	6,300,000	88,200	476,000	1991	109,000,000	1,526,000	22,645,000
1960	7,200,000	100,800	576,800	1992	116,000,000	1,624,000	24,269,000
1961	8,000,000	112,000	688,800	1993	121,000,000	1,694,000	25,963,000
1962	9,500,000	133,000	821,800	1994	133,000,000	1,862,000	27,825,000
1963	10,900,000	152,600	974,400	1995	138,000,000	1,932,000	29,757,000
1964	13,000,000	182,000	1,156,400	1996	148,000,000	2,072,000	31,829,000
1965	15,000,000	210,000	1,366,400	1997	158,000,000	2,212,000	34,041,000
1966	17,600,000	246,400	1,612,800	1998	165,000,000	2,310,000	36,351,000
1967	19,700,000	275,800	1,888,600	1999	178,000,000	2,492,000	38,843,000
1968	23,600,000	330,400	2,219,000	2000	187,000,000	2,618,000	41,461,000
1969	28,000,000	392,000	2,611,000	2001	192,000,000	2,688,000	44,149,000
1970	30,000,000	420,000	3,031,000	2002	204,000,000	2,856,000	47,005,000
1971	33,000,000	462,000	3,493,000	2003	212,000,000	2,968,000	49,973,000
1972	38,000,000	532,000	4,025,000	2004	225,000,000	3,150,000	53,123,000
1973	44,000,000	616,000	4,641,000	2005	230,000,000	3,220,000	56,343,000
1974	45,000,000	630,000	5,271,000	2006	245,000,000	3,430,000	59,773,000
1975	40,000,000	560,000	5,831,000	2007	257,000,000	3,598,000	63,371,000
1976	47,000,000	658,000	6,489,000	2008	245,000,000	3,430,000	66,801,000
1977	51,000,000	714,000	7,203,000	2009	250,000,000	3,500,000	70,301,000
1978	55,000,000	770,000	7,973,000	2010	265,000,000	3,780,000	74,081,000
1979	61,000,000	854,000	8,827,000	2011	280,000,000	3,920,000	78,001,000
1980	60,000,000	840,000	9,667,000	2012	288,000,000	4,032,000	82,033,000
1981	61,000,000	854,000	10,521,000	2013	299,000,000	4,186,000	86,219,000