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Life-cycle environmental implications of China's ban on post-consumer plastics import

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Abstract

China used to receive more than 50% of the global post-consumer plastics export, the largest share of which was PET bottles. However, China recently banned the import of foreign wastes including waste plastics. The original intention of this ban was to protect China's ecosystem quality and human health, while its environmental implications have yet to be examined. This study analyzes the life-cycle environmental impacts of this ban on post-consumer PET under a number of post-ban scenarios. Our analysis shows that the ban may substantially exacerbate environmental impacts both in China and globally, if China, in the absence of imported recyclates, increases its virgin PET fiber production using carbon-intensive coal as the feedstock. Recycling waste PET bottles within the countries that generate them to replace China's virgin PET fiber production, however, is shown to significantly reduce life-cycle environmental impacts both in China and globally. Our study highlights the potential unintended environmental consequences of the ban and the need to consider marginal technologies and their consequences in policy decisions. Our results call for cost-effective recycling infrastructure among the waste-producing countries and the mechanism to coordinate plastics recycling on a global scale.

Keywords: China; foreign waste ban; post-consumer plastics; environmental implications; life cycle assessment (LCA); consequential modeling

1. Introduction

Since the 1980s, China has been importing solid wastes from overseas in order to ease the problem of raw materials scarcity, while fueling China's manufacturing industry (Yoshida et al., 2005). China soon became the number one destination for recyclable wastes (Kellenberg, 2012). It received 7.3 Tg of post-consumer plastics from 43 different countries in 2016 alone (Brooks et al., 2018), which accounted for more than 50% of the global post-consumer plastics export. According to China Customs statistics, the largest share of waste plastics imported by China was polyethylene terephthalate (PET), representing 2.5 Tg out of 7.3 Tg of all post-consumer plastics imported in 2016 (Chen et al., 2018). Major exporters were industrialized countries including European countries, the

US, and Japan (Brooks et al., 2018).

In July 2017, the Chinese government issued a new regulation—the Implementation Plan for Prohibiting the Entry of Foreign Waste and Advancing the Reform of the Solid Waste Import Administration System (GOCSC, 2017)—that laid out the plan to ban the imports of foreign wastes from 2018. The ban lists two dozen types of solid wastes including post-consumer plastics from municipal sources. China is expanding the coverage of the initial import ban, and post-consumer plastics from industrial sources are banned from 2019.

The ban had an immediate effect on the global structure of post-consumer plastics flows (Pu et al., 2019; Wang et al., 2019); it reduced China's share in the import of plastics waste exported by G7 countries from 60% during the first half of 2017 to less than 10% during the same period a year later. The volume of plastic waste exports from G7 countries fell by 20% on average from 2017 to 2018 (Hook and Reed, 2018). The reduction in post-consumer plastics export was, however, the result of temporary measures; bales of trash piled up in the US, in the UK, in Australia, and other industrialized countries (Parker, 2018). In the short run, these recyclables are being landfilled due to the limited recycling and incineration capacities in the waste-producing countries (Hook and Reed, 2018; Qu et al., 2019). The ban already caused chaos among plastics recycling industries around the globe.

Previous literature placed its focus mainly on the global changes in flows and structure of waste plastics before and after the ban came into force. Brooks et al. (2018) indicates that China has imported a cumulative 45% of plastic waste since 1992 and estimates that 111 million metric tons of plastic waste will be displaced with the ban by 2030. Wang et al. (2020) constructed global plastic waste trade networks and analyzed the spatiotemporal evolution of the networks between 1988 and 2017. Parker (2018) indicates that the ban has redirected the waste flows to South-East Asian countries and the governments of the region are also imposing a slate of new regulations including bans, inspections, and taxes and fees. Multiple studies have also suggested that the ban may deeply affect global sustainability and calls for developing an appropriate policy framework to prevent unintended consequences (Huang et al., 2020; Qu et al., 2019; Tan et al., 2018).

The original intention of this ban was to protect China's ecosystem quality and human health (GOCSC, 2017), while the ban's life-cycle environmental implications are not all that clear. China is the largest producer of PET fiber in the world and the global demand for China's synthetic fiber remains strong. China already reached near maximum practicable collection rate for its domestically generated post-consumer PET bottles (Zhang and Wen, 2014) and 86% of China's imported post-consumer PET bottles were downcycled to produce recycled PET fiber in 2017 (Chen et al., 2018). In the absence of imported post-consumer PET recyclates due to the ban, the country needs to either increase the use of virgin materials or reduce the domestic production of PET fiber (Yoshida et al., 2005).

Moreover, China is increasingly reliant on coal for its PET fiber production. PET resin, synthesized through the polymerization reaction of purified terephthalic acid (PTA) and ethylene glycol (EG), is widely used to produce fiber, bottles, sheet, film, and engineering resin (Chen et al., 2018). PET resin is traditionally derived from petroleum resources (Scheirs and Long, 2005). In China, however, the use of abundant and inexpensive coal instead of petroleum for chemical production has been encouraged by the government, and as a result, the production of EG is increasingly relying on coal as the feedstock, which comes with its own environmental costs (Yang et al., 2018). Production of PTA still uses petroleum feedstock in China. In this article, 'Coal-based' PET fiber production pathway refers to the production pathway that uses petroleum-based PTA and coal-based EG as the feedstock, whereas the 'Petroleum-based' counterpart to that uses both petroleum-based EG and PTA (see section 2 of the Supplementary Material).

To quantify the possible environmental impact of this ban, we designed a number of post-ban what-if scenarios based on possible market conditions. Under the assumption that the amount of global PET fiber production is kept equal in all scenarios, the change in environmental impact before and after the ban coming into force is caused by using different feedstocks to produce PET fiber. Therefore, we quantified and compared the environmental impacts of various PET fiber production pathways by using the life cycle assessment (LCA) (ISO, 2006a, b) approach.

2. Materials and Methods

2.1. Scenario design

Currently, a significant portion of the post-consumer PET bottles used to be imported by China prior to the ban, which amounts to 2.5 Tg yr^{-1} (Chen et al., 2018), is being landfilled or stored within the countries that generate them or sent to other countries. As a result, the ban creates a shortfall of feedstock for PET fiber production in China, which is estimated to be about 2 Tg yr^{-1} that were produced using imported post-consumer PET bottles prior to the ban. The difference, about 0.5 Tg yr^{-1} or 20% of the PET recyclate input, was the portion lost during the process, which was generally landfilled (Nakatani et al., 2010).

Our baseline scenario represents the conditions prior to the ban. We created three what-if scenarios post the ban. Given that the waste plastic recycling industry is currently undergoing drastic changes, these scenarios serve as an instrument to gauge the range of possible futures and are not meant to be used as projections. Therefore, we intentionally explored extreme conditions, while the reality is likely to reside in-between the scenarios that we evaluated. In all scenarios, the amount of PET fiber production at the global level is kept equal to fulfill human needs. The baseline scenario, i.e., *business as usual scenario prior to the ban*, ('BAU-prior', see Fig. 1a) follows the conditions prior to the ban where 2.5 Tg of waste PET plastics are imported by and recycled in China to produce 2 Tg of recycled PET fiber. Three post-ban scenarios assume that the shortfall of the 2 Tg of recycled PET fiber that used to be produced in China is fulfilled by either China's marginal virgin fiber production, or by recycled PET fiber production within the countries that generate post-consumer PET bottles (hereafter 'Exporters').

Among three post-ban scenarios, the current market response to the ban is the most closely aligned with the case where Exporters landfill, stack up, or send to other nations the 2.5 Tg of post-consumer PET bottles (Hook and Reed, 2018) and China makes up the 2 Tg shortfall in recycled PET fiber using virgin feedstock, which, in China, is increasingly relying on coal (Yufang and Ming, 2011). This scenario is referred to as *Business as usual scenario post the ban* ('BAU-post' scenario, see Fig. 1b) in this paper. Under the *local recycling-substituting domestic fiber scenario* ('LR-substituting domestic', see Fig. 1c), the shortfall of the 2 Tg of PET fiber is made up by China's virgin PET fiber production, as was is in the 'BAU-post' scenario, whereas the 2.5 Tg of post-consumer PET plastics are locally recycled, rather than landfilled or piled up, within the waste-producing countries, replacing

2 Tg of domestic virgin fiber production, which is based mostly on petroleum feedstock. Lastly, the *local recycling-substituting Chinese fiber scenario* ('LR-substituting CN', see Fig. 1d) follows the same conditions as the 'LR-substituting domestic' scenario, except that the PET fiber produced through local recycling within Exporters replaces China's virgin PET production, not the domestic ones.

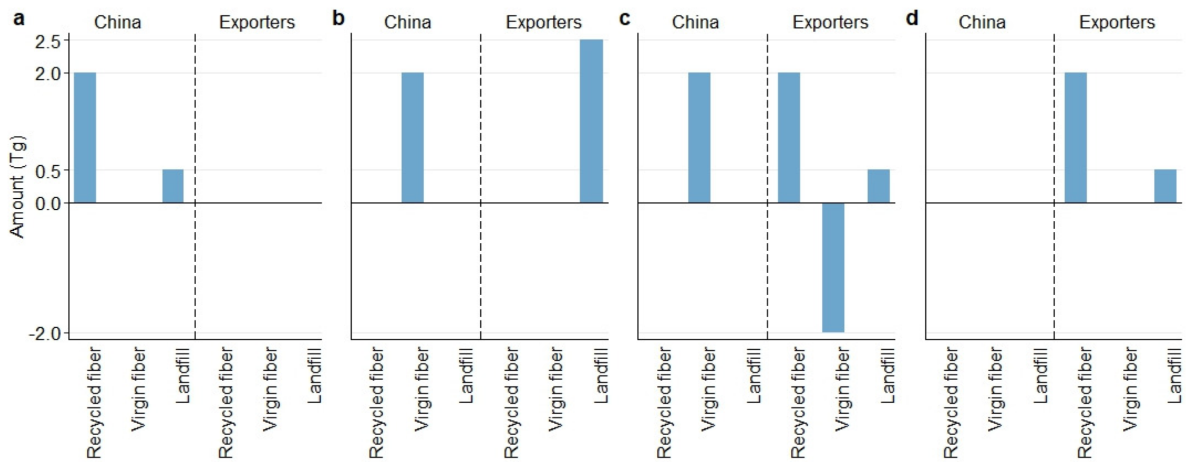

Fig. 1. The fate of post-consumer PET bottles under the main what-if scenarios before and after the ban. a, Business as usual scenario prior to the ban ('BAU-prior') where imported post-consumer PET bottles are used to produce recycled PET fiber in China. **b**, Business as usual scenario post the ban ('BAU-post') where the shortfall of the 2 Tg of PET fiber is fulfilled by virgin fiber in China marginally supplied by the coal-based pathway, and the 2.5 Tg of post-consumer PET bottles are landfilled or piled up in the countries producing them. **c**, Local recycling-substituting domestic fiber scenario ('LR-substituting domestic'), under which post-consumer PET bottles are recycled within the countries of generation to replace their domestic virgin fiber production. **d**, Local recycling-substituting Chinese fiber ('LR-substituting CN'), under which post-consumer PET bottles are recycled within the countries of generation to replace China's virgin fiber production.

2.2. Life-cycle environmental impacts calculation

CO_2 and major air pollutant emissions of each PET fiber production pathway or under each scenario are quantified using LCA methodology, a tool to assess the potential environmental impacts and resources used throughout a product's life cycle (Foolmaun and Ramjeeawon, 2013; ISO, 2006b). The value of LCA to quantitatively assess products' life-cycle environmental impacts has been recognized and it is increasingly used to support decisions in policy and government arenas (Kirchain Jr et al., 2017).

The process-based matrix inversion method is employed as the computational approach (Suh and Huppes, 2005) and summarized as equation (1-4).

$$M = BA^{-1}Y \quad (1)$$

$$N = MC \quad (2)$$

$$M_i^* = (B + \delta B_i)(A + \delta A_i)^{-1}Y \quad (3)$$

$$N_i^* = M_i^* C \quad (4)$$

B	Elementary flow matrix
A	Intermediate flow matrix
Y	Final demand matrix
M	Life cycle inventory matrix
C	Characterization vector
N	Environmental impact matrix
δB_i	Randomly sampled deviation matrix for the elementary flows
δA_i	Randomly sampled deviation matrix for the intermediate flows
i	Number of simulation, $i = 1, \ldots n$ (n = 1000)
M_i^*	Life cycle inventory matrix under the *i* round of Monte Carlo Simulation
N_i^*	Environmental impact matrix under the *i* round of Monte Carlo Simulation

To allocate environmental burdens among different useful lives of the material, we adopt the cut-off rule (Shen et al., 2010), which has been widely applied for recycled or recovered products. Under the cut-off approach, all virgin material production burdens are assigned to the first use of the material and the burdens assigned to the recycled resin system begin with the recovery of post-consumer PET bottles. Monte Carlo simulation is used to deal with uncertainty (Gregory et al., 2016; Suh and Qin, 2017) and we do 1,000 times of simulations (Qin and Suh, 2017). Section 3 of the Supplementary Material provides more information about uncertainty analysis of this research.

(a) Life-cycle environmental impacts of each production pathway

We define the functional unit as "one kilogram of PET fiber" for the recycling pathway in China, the coal-based pathway in China, the recycling pathway in Exporters, and the petroleum-based pathway in Exporters and as "landfilling one kilogram of post-consumer PET bottles" for post-consumer PET bottle treatment. Thus, the final demand matrix can be expressed as Y_0. Each column vector in Y_0 represents the final demand vector of one PET fiber production pathway.

$$Y_0 = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (5)$$

Columns: CR, CV, ER, EV, L. Rows:

- Recycled PET fiber production in China
- Coal-based virgin PET fiber production in China
- Recycled PET fiber production in Exporters
- Petroleum-based virgin PET fiber production in Exporters
- Landfilling post-consumer PET bottles

Y_0 Final demand matrix, each column vector represents the final demand vector of one production pathway

* 'CR' represents the recycling pathway in China; 'CV' represents the coal-based virgin PET fiber production pathway in China; 'ER' represents the recycling pathway in Exporters; 'EV' represents the petroleum-based virgin PET fiber production pathway in Exporters; 'L' represents post-consumer PET bottle landfill.

The intermediate flow matrix and elementary flow matrix of coal-based EG production, virgin PET fiber production, and recycled PET fiber production are provided by three companies in China (foreground data is shown in the Supplementary Excel file). Bottle-to-fiber recycling mainly includes mechanical recycling and chemical recycling (Achilias and Karayannidis, 2004; Shen et al., 2010). In chemical recycling, PET polymer is broken down into monomers or oligomers, so the recycled polymer has very similar or even identical properties with virgin polymer (Shen et al., 2010). The company providing process data on recycled PET fiber production for us adopts chemical recycling technology. Data on other processes is collected from the ecoinvent V3.4 database (Wernet et al., 2016), which is currently the most widely used life cycle inventory database. Miscellaneous materials, which account for less than 1% by weight of the net process inputs, are typically cut off unless inventory data for their production are readily available (ERG, 2011).

Given that air quality and climate change are the main foci of the Chinese government's environmental management, we selected the major air pollutants of concern: CO_2, PM2.5, SO_2, and NOx (Wang and Hao, 2012). As for the life cycle environmental impact categories, we used ReCiPe Endpoint 2016 (Huijbregts et al., 2017) that covers all three areas of protection, namely, human health damage, ecosystem quality, and resource scarcity.

(b) Life-cycle environmental impacts under each scenario

Based on the scenario design, the final demand matrix under the four scenarios is expressed as Y_s. Each column vector represents the final demand vector of one scenario.

$$
\begin{array}{c}
\begin{array}{cccc} \text{S1} & \text{S2} & \text{S3} & \text{S4} \end{array} \\
Y_s = \begin{pmatrix} 2 & 0 & 0 & 0 \\ 0 & 2 & 2 & 0 \\ 0.5 & 0 & 0 & 0 \\ 0 & 0 & 2 & 2 \\ 0 & 0 & -2 & 0 \\ 0 & 2.5 & 0.5 & 0.5 \end{pmatrix}
\begin{array}{l} \text{Recycled fiber production in China} \\ \text{Coal-based virgin fiber production in China} \\ \text{Landfilling post-consumer bottles in China} \\ \text{Recycled fiber production in Exporters} \\ \text{Petroleum-based virgin fiber production in Exporters} \\ \text{Landfilling post-consumer PET bottles in Exporters} \end{array}
\end{array}
\qquad (6)
$$

Y_s Final demand matrix, each column vector represents the final demand vector under one scenario

* 'S1' represents the 'BAU-prior' scenario; 'S2' represents the 'BAU-post' scenario; 'S3' represents the 'LR-substituting domestic' scenario; 'S4' represents the 'LR-substituting CN' scenario. Unit: Tg.

To quantify the environmental impact changes occurring in China under each scenario as compared to the case before the ban, we distinguish the impacts occurring in China and the rest of the world for the recycling pathway in China since the impacts of collection & sorting and sea transportation of post-consumer PET bottles occur in the rest of the world and impacts of transforming post-consumer PET bottles to recycled PET fiber occurs in China.

3. Results

3.1. LCA results

Given the inherent uncertainties in the parameters used in our study, we ran a Monte Carlo simulation, and the results are expressed as a distribution. Our LCA results (Fig. 2) show that producing 1 kg of virgin PET fiber from petroleum feedstock in exporting countries emits on average 2.4 kg of CO_2 throughout its life-cycle. Under the current technological configurations, producing 1 kg of PET fiber in China using PET recyclates is estimated to generate 1.6 kg of CO_2 throughout its life-cycle. However, 1 kg of coal-based virgin PET fiber produced in China, is estimated to emit 3.9 kg of CO_2 emission. For exporting countries, producing 1 kg of recycled PET fiber by recycling their own post-consumer PET bottles emits 1.3 kg of CO_2, which is 0.3 kg less than that from recycled PET fiber produced in China.

Furthermore, coal-based virgin PET fiber in China shows 38-246% higher PM2.5 SO_2 and NOx emissions as compared to recycled PET fiber in China. Recycled PET fiber in exporting countries reduces major air pollutant emissions by 44-67% as compared to the recycled PET fiber in China, partly owing to the cleaner power supply in developed countries and partly because of the avoided carbon emission from shipping post-consumer PET bottles to China. Coal-based virgin PET fiber produced in China shows 80-300% higher life-cycle air pollutant emissions as compared to petroleum-based PET fiber.

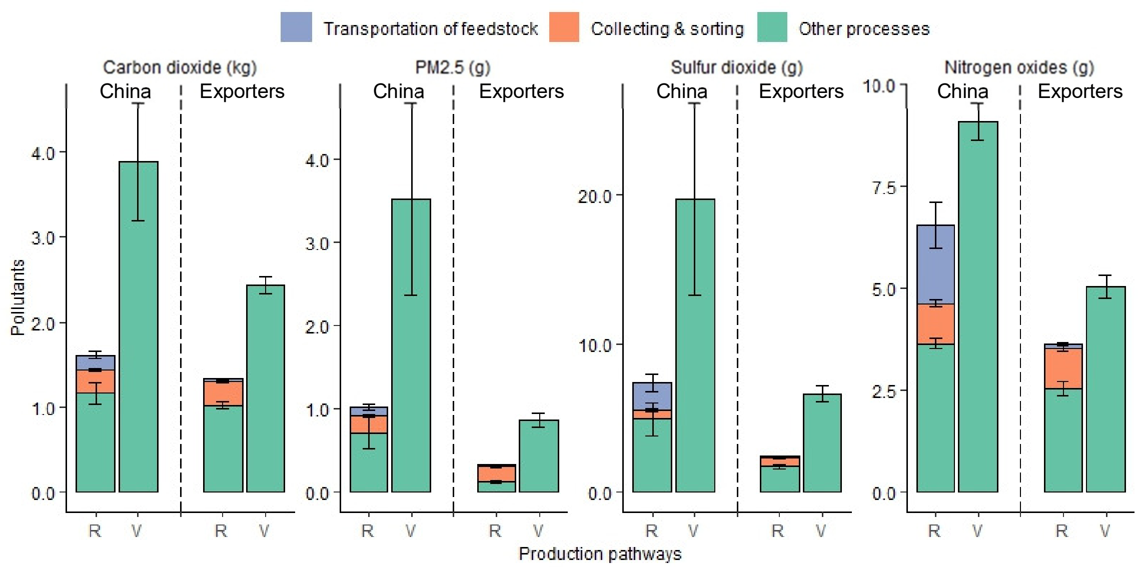

Fig. 2. Life-cycle CO_2 and other major air pollutant emissions of PET fiber production pathways per kg of PET fiber. Each bar represents pollutant emissions of one PET fiber production pathway. 'R' under China is recycling pathway; 'V' under China is coal-based virgin PET fiber production pathway; 'R' and 'V' under Exporters are recycling pathway and petroleum-based virgin PET fiber production pathway, respectively, within Exporters. The error bars are the standard deviation calculated over 1,000 times of runs using Monte Carlo simulation.

3.2. Scenario analysis results

Given the uncertainties in the underlying parameters, we have performed Monte Carlo simulation, and the results are presented in box plots (Fig. 3). Under the 'BAU-post' scenario, the average life-cycle CO_2 emissions increase by 5.4 Tg yr^{-1} in China (Fig. 3a) due primarily to the increase in carbon-intensive, coal-based PET fiber production. At the global level, the ban reduces international shipment, sorting activities, and associated emissions for post-consumer PET bottles. However, the reduction in shipping and sorting activities does not negate the increase in life-cycle emissions from coal-based PET fiber production, resulting in a net increase of life-cycle CO_2 emissions by 4.5 Tg yr^{-1} on the global scale (Fig. 3b). Likewise, life-cycle emissions of other major air pollutants including PM2.5, SO_2, and NOx increase both in China and globally under the 'BAU-post' scenario (Fig. 3).

If the 2.5 Tg yr^{-1} of post-consumer PET bottles are recycled locally within the countries where they are generated substituting domestically produced virgin PET fiber, global life-cycle CO_2 emissions are reduced from the 'BAU-post' case roughly by half to on average 2.3 Tg yr^{-1} (Fig. 3b), because producing 1 kg of recycled PET fiber within Exporters generates only about 1.3 kg of CO_2 emissions as compared to the 2.5 kg from petroleum-based virgin PET fiber within Exporters (Fig. 2). This scenario, i.e., 'LR-substituting domestic' scenario in this paper. Life-cycle emissions within China do not change under this scenario as compared to 'BAU-post', as the substitution of virgin PET fiber by recycled PET fiber is assumed to take place within Exporters. Under both scenarios, i.e., 'BAU-post' and 'LR substituting domestic', life-cycle emissions of major air pollutants including CO_2, PM2.5, SO_2, and NOx increase both in China (Fig. 3a) and globally (Fig. 3b) as compared to the case prior to the ban.

However, when post-consumer PET bottles are recycled within Exporters to produce PET fiber *and* if the recycled PET fiber from Exporters replaces the virgin PET fiber produced in China, on average 2.3 Tg yr^{-1} and 0.6 Tg yr^{-1} reductions in CO_2 emission are expected in China and in the world, respectively, as compared to the case prior to the ban. This scenario, i.e., 'LR-substituting CN' scenario in this paper, reduces not only CO_2 emissions but also other major air pollutants throughout the life-cycle (Fig. 3). This is mainly due to the lower life-cycle emissions of recycled PET fiber within Exporters as compared to virgin or recycled PET fibers produced in China. The difference in life-cycle emissions is attributable in part to the cleaner power supply in Exporters and to the avoided pollutant emissions from shipping and handling of post-consumer PET bottles to China (Fig. 2).

Overall, 'LR-substituting CN' scenario presents the most favorable environmental outcomes among the three major post-ban what-if scenarios examined. It is, however, questionable whether locally recycled PET can successfully outcompete China-produced virgin PET fiber under the current market conditions, given the high cost of recycling among industrialized countries.

In addition to these results, we have obtained additional results based on additional end-point indicators of Life Cycle Impact Assessment (Pennington et al., 2004) and scenarios, which are presented in section 4, Robustness Check, of the Supplementary Material.

China's import ban greatly affected the global landscape of plastics recycling. Our research focuses on the environmental implications of the ban taking waste PET recycling as an example. More research is needed to understand the social and economic implications of this ban including but not limited to occupational health and safety and child labor. Moreover, the implications of banning other plastics (such as PP, PE, and PVC) merit further research.

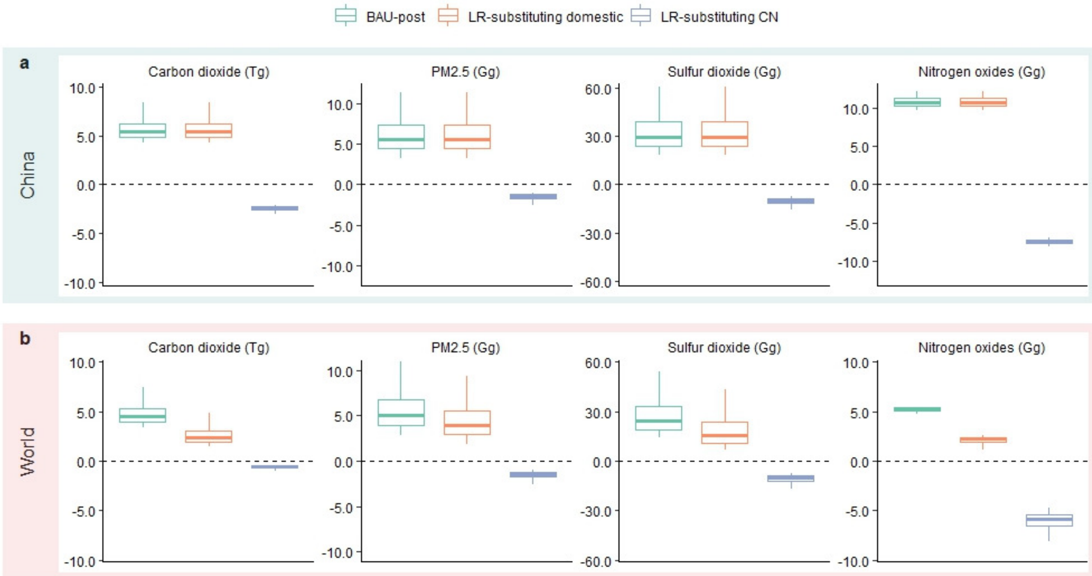

Fig. 3. Changes in China's and global annual CO_2 and other major air pollutant emissions under each scenario as compared to the case before the ban. a, changes in China. **b**, changes at the global level (including China). 'BAU-post' represents the Business as usual scenario post the ban where the shortfall of recycled PET fiber is fulfilled by virgin fiber production in China marginally supplied by the coal-based pathway, and post-consumer PET bottles are landfilled in the countries producing them; 'LR-substituting domestic' represents the scenario where post-consumer PET bottles are recycled within the countries of generation to replace their domestic virgin fiber production; 'LR-substituting CN' represents the scenario where post-consumer PET bottles are recycled within the countries of generation to replace China's virgin fiber production. Positive values and negative values indicate increases and decreases in emissions, respectively, as compared to the 'BAU-prior' scenario. Boxplots show medians (horizontal lines), 25th and 75th percentiles (upper and lower box limits), and extreme observations (bars) based on 1,000 runs of Monte Carlo Simulation.

4. Conclusions and policy implications

The original intention for the government of China to prohibit the imports of solid wastes was to protect its ecosystem quality and human health (GOCSC, 2017). But our study on PET, which constitutes the largest portion of the imported waste plastics prior to the ban, indicates that the ban may exacerbate environmental impacts both in China and globally. Even if the entire amount of post-consumer PET bottles that were exported to China are locally recycled within the countries where they are produced, life-cycle emissions of major air pollutants and impacts are likely to increase as compared to the case prior to the ban. Only under the unlikely scenario where virgin PET fiber produced in China is replaced by recycled PET fiber produced locally within industrialized countries, life-cycle emissions of major air pollutants and environmental impacts are reduced.

As such, we believe that the ban is unlikely to achieve its intended objectives. This likely misfire of the ban is rooted in the lack of marginal thinking in policy design (Kätelhön et al., 2016; Kätelhön et al., 2015); the ban creates a shortage in recyclate feedstock for PET fiber production in China, which is likely to be fulfilled by the marginal technology for virgin PET production that uses coal-based pathway. It is important to acknowledge that, however, the ban may alleviate other pressing issues such as occupational health and safety and child labor, which were not quantified in this study.

For China, we recommend a comprehensive re-evaluation of the policy considering marginal technologies that will be utilized as a consequence of the ban. Building modern recycling facilities while selectively allowing the import of high-quality recyclable PET, rather than an outright ban might be a possible alternative (Tan et al., 2018).

Our study indicates that the adverse environmental impacts of the ban are associated mainly with the use of coal-based PET production. Coal-based chemical industry is rapidly expanding in China; in addition to the coal-based EG production, coal-to-aromatics technology may soon be able to develop coal-to-PTA technology on a commercial scale, enabling an entirely coal-based PET fiber production pathway (both PTA and EG based on coal; see section 2 of the Supplementary Material for details). Producing both PTA and EG out of coal would show an even stronger economic advantage (Li et al., 2017)—and environmental disadvantage—over petroleum-based PET fiber production pathway. Addressing the severe air pollutions associated with coal-based chemical production in China would, therefore, be urgently needed before its mass-deployment.

For waste-producing countries, there is an urgent need to rapidly increase the capacity to recycle end-of-life PET bottles cost-effectively (Walker, 2018). Currently, cost-competitive PET bottle recycling within industrialized countries is a challenge. In the meantime, policymakers may consider incentivizing the development of domestic infrastructure for PET recycling through e.g., taxing virgin materials and taxing landfill of recyclable materials. Even if the amount of post-consumer PET bottles that were used to flow to China before the ban is completely recycled within the countries that generate them, the ban's adverse impacts on the environment, especially those within China, are likely to persist. That is because locally recycled PET bottles within industrialized countries are more likely to replace only locally produced virgin PET fiber, not the virgin PET fiber produced in China derived from coal. Our results, therefore, suggest that closing the loop, or increasing material circularity of PET within each country, alone may not negate the adverse impacts of the ban on the environment unless the global economy institutes a mechanism under which heavily polluting processes are eliminated in the supply chain regardless of where they are located; as long as the process with higher pollution intensity enjoys price advantage over more environmentally benign process, global market will favor the pollution-intensive process wherever it is. Our analysis did not consider the case where waste plastics flowing into the least developed countries, in which case the environmental consequence of the ban may well be far worse than any of the scenarios tested in our study. To prevent problem-shifting from one country to another, a mechanism to coordinate plastics recycling on a global scale is in urgent need (Qu et al., 2019). Creating the framework conditions under which the market favors environmentally benign technologies over pollution-intensive ones demands a durable and global mechanism to internationalize environmental externalities. A global level playing field in environmental tax and carbon pricing schemes, for example, would be a key to create such framework conditions (Nordhaus, 2011). Neither political appetite nor the international governance structure that can enforce a global mechanism to internalize externalities exists today, leading to a large disparity in e.g., carbon prices across the world (World Bank, 2018). In the meantime, other opportunities including more aggressive application of pollution abatement technologies and tightening emissions standards targeting heavy polluters should continue to be pursued.

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Supplementary Material

fig. S1. Material flow analysis of non-fiber PET among ten world regions and over its life cycle in 2016.
fig. S2. PET fiber production pathways using different raw materials.
fig. S3. Life-cycle endpoint impacts of PET fiber production pathways per kg of PET fiber.
fig. S4. Changes in China's and global annual endpoint impacts under each scenario as compared to the case before the ban.
fig. S5. The fate of post-consumer PET bottles under the possible what-if scenarios in robustness check.
fig. S6. Changes in China's and global annual major air pollutant emissions and endpoint impacts under the possible what-if scenarios in robustness check.
data file S1. Sources, geographical appropriateness, and uncertainty information of life cycle inventory data (Excel file).