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Pollution reduction by rationalization hypothesis and water pollution in China

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This paper empirically investigates pollution reduction by rationalization hypothesis in China. We study the heterogeneous firm's export effect on water pollution in China. We use China's firm-level data from 2000 to 2012 to estimate the firm's heterogeneity of export effect, composition effect, and technique effect on water pollution. We find that intra-industry agglomeration produces a competition effect, and more productive firms can export with less polluted water. More productive firms can export with less polluted water by reallocating more productive labor from dirty firms. We find an inverted U-shaped relationship between a firm's productivity and water pollution. Intra-industry agglomeration drives up labor productivity; higher productive firms export while producing more polluted water initially. When a firm's productivity is increasing, export activity produces less polluted water. More export induces less water pollution for high productivity firms. We conclude that the mechanism of pollution reduction by rationalization hypothesis does exist for water pollution in China. Trade liberalization causes some firms to become cleaner, even though we observe relatively clean exporting firms and relatively dirty domestic producers at different productivity stages. Productivity-induced rationalization causes water pollution to fall with high firm productivity. Water pollution in different regions has disparities. Eastern area in China is more likely to produce more polluted water than the rest of China.

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Introduction

China, as one of the major manufacturing hubs and top trade players in the world market, only occupies very limited water resources. Despite its economic role in the world, China has only 6% of the world's freshwater resources.[1] The per capita water resource of China is actually below the water average and only one-fifth of the US average. However, on the other side, China's water pollution is serious. In 2020, according to China's Ministry of Ecology and Environment report, 0.6% of surface water cannot be used for any purpose; 5.4% of lake water cannot be used for any purpose. One of the most important water pollution sources is from industrial production. China is facing a water scarcity challenge.

We want to solve the practical problem of water pollution and trade above. We do know air pollution and trade policy from existing literature. In terms of water pollution and trade, the academic field raises less concern. In many developing countries, such as China and India, pollution heaven is a dominant argument. However, in terms of water pollution, the view is vague. How does a firm respond to the trade openness on water pollution? Does industrial agglomeration make water pollution worse when firms have to do international trade? Why does trade provide an incentive to some firms to pollute more and some pollute less water? Which firms gain from trade while undertaking water pollution?

The determinants of pollution and trade are one of the most essential issues in international environmental economics. Although there are a large number of literatures concerning this topic, existing research typically considers aggregated effect of trade on pollutants. In contrast, this paper is analytical, setting out a simple empirical model to answer those questions above. We develop an extended empirical model with disaggregated data to portray the mechanism of water pollution sources and differentiate firms according to *labor productivity* and *agglomeration*.

In this paper, we propose a mechanism that links *intra-industrial* agglomeration, firm productivity, *factor reallocation*, and *water pollution*. First, in an environment with heterogeneous firms, the fundamental force that drives a firm's productivity is agglomeration. We follow the span of intra-industry agglomeration to investigate the resource reallocation among firms in the same industry. We argue that production factors within the same industry are relatively easy to reallocate among different firms. Second, with trade, high-productivity firms can export, so high-productivity firms need to produce more with water pollution. Productive firms suffer from an increase in water pollution initially since the output of the production increases. After trade, high-productivity firms absorb labor and other production factors from low-productivity firms, which is a reallocation of resources. Then, with the firm's productivity growing, high-productive firm's water pollution will decrease with access to trade. As a consequence, more productive firms can export with less polluted water when the firm's productivity achieves a certain level.

To motivate our empirical model, with the development of heterogeneous firm theory by Melitz (2003), aggregated regional-level investigation can be extended to the firm level. This paper combines approaches from different parts of the trade and pollution literature to provide evidence to find water pollution sources. Cherniwchan et al. (2017) raise three new hypotheses, which are the pollution reduction by rationalization hypothesis (PRR), the distressed and dirty industry hypothesis, and the pollution offshoring Hypothesis. A common feature of the three new hypotheses is to concentrate on firm heterogeneity. The three new hypotheses are developed based on three old hypotheses. Traditional trade and environmental research focus on the environmental Kuznets curve, competitiveness hypothesis, and pollution haven hypothesis, which is summarized as "three old

hypotheses". One of the common features of the three old hypotheses is to concentrate on aggregated data at the national or regional level.

In this paper, we use water pollution at the firm level to test PRR empirically. PRR links market share reallocations and selection effects in the Melitz (2003) model to changes in industrial emissions. It differentiates firms into dirty firms and clean firms with different productivity. We want to estimate the PRR hypothesis. We investigate whether trade can drive water pollution down as dirty firms exit from the international market and resources and inputs are reallocated to clean firms whose productivity can be increased. We want to analyze whether trade makes the dirtiest firms exit and whether the source is reallocated to the cleanest firms. Therefore, the research question in our paper is what the effect of a firm's productivity on a firm's water pollution is with the export effect.

Literature review

Our paper is related to the literature on trade and environment. For example, Cole and Elliott (2003) find trade-induced composition effect is small relative to scale technique effects. Cole (2004) demonstrates that pollution haven effects are only a small proportion of pollution than other factors. If income differences are substantial across countries, free trade can raise world pollution (Copeland and Taylor, 1995). Dardati and Saygili (2021) conclude exporters can be cleaner if total sales instead of value added is used for measuring output. Exporting firms can benefit the environment more than non-export firms (Banerjee et al., 2021). EU and the USA outsource the largest polluted water to other regions (Wiedmann and Lenzen, 2018). Holladay (2016) finds that the US export plants emit less than non-exporters. In contrast to these general pollution studies, our paper focuses on a particular pollutant to analyze production resource reallocation.

Within this line of research, studies show that the environment can benefit from trade at an aggregated level. Generally, free trade is good for the environment (Antweiler et al., 2001; Forslid et al., 2018). For example, Thompson and Jeffords (2017) find that trade and water-intensive imports can actually decrease water pollution. However, countries at different economic stages show different relationships between trade and pollution. Zugravu-Soilita (2018) concludes that trade intensity decreases CO_2 emission but increases water pollution in Central and Eastern Europe and the Commonwealth of Independent States. Cherniwchan (2017) finds that NAFTA actually decreases the emission of PM_{10} and SO_2 from US manufacturing sectors. In the case of China, developing countries are more effective in reducing carbon and sulfur dioxide emission intensity through trade, and the case is especially true for China argued by Ma and Wang (2021). Cui et al. (2020) argue that China's accession to WTO decreases SO_2 emissions, but Lin (2017) finds that trade actually increases air pollution in China. He and Wang (2020) find that China's processing exporter generates lower pollution, and exporters can gain more from adopting new clean technology. Exporting firms are more environmentally friendly than non-exporting firms in China (Pei et al., 2021).

This trade and environment literature typically assumes industrial aggregated production with comparative advantage at the country level. To further investigate the pollution source and differentiate pollution type, in contrast, our paper studies water pollution from the effect of trade, which is different from existing research pollutants. Different from existing literature, which only focuses on aggregated water pollution, our research seeks to investigate further the firm-level channels of the effect of trade on wasted water.

In the existing literature, composition effect, scale effect, and technique effect are the basic channels to construct the theoretical framework of trade and environment. Hence, endowments, production and income are centered in the studies of trade and environment. Karp (2011) provides a thoughtful review of work transforming trade and environmental theoretical research from partial equilibrium to general equilibrium. Cherniwchan et al. (2017) provide a recent literature review to transform the new three firm-level hypotheses and merge firm heterogeneity into the trade and environment research framework. A very interesting effect of heterogeneous firms with intra-industry trade plays a role in trade and pollution emission. LaPlue (2019) argues the increase in firm productivity will increase output, reduce aggregate emission intensity and reconcile the cross-sector resource to a more productive firm. Qi et al. (2021) argue that larger firms are more likely to use clean water technology in China. To account for these features, our paper extends firm productivity with three effects, so the three effects actually construct the framework for our empirical investigation.

Further studies continue with the role of environmental regulations on trade and pollution. Gani and Scrimgeour (2014) argue that the governess can decrease industrial water pollution; the governess includes the rule of law, regulatory quality, and control of corruption. Domestic institutions but not environmental clauses in preferential trade agreements induce trade distribution of environmental burdens, as argued by Kolcava et al. (2019). National level policy cannot work well for some pollutants. For example, water pollution from manufacturing should be regulated internationally (Carrascal Incera et al., 2017). Egger et al. (2021) find that tighter environmental policy can reallocate labor toward exporting firms and improve export firms' average productivity. Duan et al. (2021) argue that environmental regulations can be a source of comparative advantage, but productivity and trade costs decrease the effects of environmental regulations on production and trade. Song et al. (2021) extend the study of environmental regulations to the labor market and find that environmental technology actually promotes regional labor supply and demand. Brunel (2017) argues that the EU has strict environmental regulations, but the EU actually produces more pollution-intensive goods and progressively imports less pollution-intensive goods. The wastewater discharge plays a role to stop new firms to pollute water, and productive pollution firms can get a larger export market (Zhang et al., 2020). Shapiro and Walker (2018) argue that the reduction of pollution in the US is the case of the pollution tax, not trade, from 1990 to 2008. He et al. (2020) argue that environmental regulations in China reduce firms' TFP and cost huge economically. Wang et al. (2023) argue that low-productive firms with high pollution tend to move to the upstream stage in the global value chain while facing stricter water regulations.

In our paper, the role of environmental regulations on water is also included. In contrast, at the firm level, in our model, the environmental institutions are implemented as water-purified equipment. This is also the unique difference of water pollution comparing to other pollutants.

We cannot ignore the economic growth in the framework of trade and environment. Bretschger and Karydas (2019) developed a basic climate economic (BCE) model and it shows the impact of climate change and climate policy on economic development. Copeland and Taylor (2004) argue that environmental costs should be internalized to better analyze the welfare of trade. Jayachandran (2021) notes economic development affects the environment. Economic gains and environmental costs from trade can be spatially different. Zhang et al. (2019) find that coastal regions gain more economically and emit less in China, while inland regions perform exactly the opposite. Empora et al.

(2020) find a positive nonlinear relationship between emission and output, which is different from the Environmental Kuznets Curve's U-ship for the case of the USA. Lee et al. (2010) argue that the Kuznets curve hypothesis for water pollution only exists in America and Europe, not in Asia, Africa, and Oceania. In our empirical model, we borrow the idea of economic cost and environmental gains to construct an empirical model. In contrast, we use firm-level production factors such as economic cost and water pollution as environmental loss instead of using aggregated data.

Existing literature does a very good job of explaining the relationship between trade and the environment at the industry level or country level with aggregated data. However, the research on the heterogenous firm's trade-induced pollution response has not been well documented. The existing study on water pollution is even less. In this paper, we investigate empirically the Pollution Reduction by Rationalization Hypothesis (Cherniwchan et al., 2017). We study the role of trade reallocation of endowments between dirty firms and clean firms on water pollution in China. By focusing on comparative advantages for pollution-intensive goods, we can identify whether trade can improve a firm's environmental performance or worsen it in terms of water usage. We first investigate the effect of intra-industrial agglomeration on a firm's productivity. Then, we analyze the effect of the firm's productivity on the firm's wastewater.

The remainder of the paper is structured as follows. In the next section, we introduce our empirical strategy following the logic of PRR and data description. Then, we present the estimated results with a discussion about the relationship between intra-industry agglomeration, firm productivity, and trade. In extensive discussions, we especially discuss the mechanism of resource reallocation and trade as well as the spatial distribution of water pollution and trade in China. The last section concludes and outlines some policy implications.

Empirical model

The key issue of our paper is to investigate the PRR hypothesis for water pollution. The important extension of our model is to focus on the firm's heterogeneity with export effect. Traditionally, agglomeration can affect environmental pollution through scale effect, composition effect, and technology spillover effect. If agglomeration affects water pollution through the technique effect, pollution can be decreased by the technique effect, not by the firm's trade. This would indicate that trade cannot make firms become cleaner. Then there will be no need to test PRR. We study the firm's performance on water pollution. In summary, our empirical model's construction is based on the approach of a firm's productivity on the environment with export effect.

Model specifications. To validate our theoretical framework mentioned in the section above, we need to test the role of agglomeration on productivity. We use a two-stage estimation technique.

In the theoretical conceptual framework, we argue that intra-industrial agglomeration drives a firm's productivity. Intra-industrial agglomeration will produce a competition effect and affect the firm's productivity. Therefore, we need first study the mechanism of effect of agglomeration on firm's productivity. We use first model in the following to study the role of agglomeration on firm's productivity.

Then, we follow up with Cherniwchan et al. (2017) to investigate whether a firm's productivity will play a role in a firm's water pollution. High-productive firms can export and low-productive firms do not export. More productive firms can get more production resources from less productive firms and export

to the international market. Trade liberalization will make some firms enter, and some firms exit the market. At first, the firm's water pollution will increase since exporting to the international market will increase production size and produce more wastewater. Then firm's productivity continues to increase and water pollution abatement also increases, then water pollution will decrease. We use the second model in the following to analyze the role of a firm's productivity and export on a firm's water pollution.

Hence, the first model provides a tool to analyze competition effect of intra-industrial agglomeration on firm's productivity. The second model is based on the first model to validate the effect of productivity and export on water pollution.

In the baseline model, we first test the role of agglomeration on a firm's productivity.

$$
\begin{aligned}
\text{Productivity}_{it} = {} & \beta_0 + \beta_1 \text{agg}_{cjt} + \beta_2 \text{agg}_{cjt}^2 + \beta_3 \text{grad}_{ct} \\
& + \beta_4 \text{FDI}_{ct} + \beta_5 \text{export}_{it} + \beta_6 \text{KL}_{it} \\
& + \beta_7 \text{wage}_{it} + \beta_8 \text{empl}_{it} + \epsilon_{it}
\end{aligned}
\tag{1}
$$

We follow the work by Copeland and Taylor (2013) as the basic theoretical framework. Then, we combine Copeland and Taylor (2013) with a recent work on heterogeneous firms by Cherniwchan et al. (2017). Our empirical mechanism to test PRR allows us to link productivity, trade and pollution. Moreover, we need to seek the motivation to have heterogeneous firms with different levels of productivity. That is why we need to design two-stage models as our empirical strategy.

The basic logic for constructing Eq. (1) is to investigate the role of agglomeration in determining a firm's productivity. A firm's productivity is determined by city-level characteristics that the firm locates, as well as firm-level characteristics. Hu et al. (2015), Hoang and Schiller (2023), and Greenaway and Kneller (2008) argue the firm's productivity can be determined by agglomeration that the firm locates and also some firm-level determinants, such as wage, export status, size, etc.

Then, we test the role of a firm's productivity on water pollution. We try to validate Pollution Reduction by Rationalization hypothesis. Following the framework, we estimate:

$$
\begin{aligned}
E_{it} = {} & \alpha_0 + \alpha_1 \text{productivity}_{it} + \alpha_2 \text{productivity}_{it}^2 + \alpha_3 \text{export}_{it} + \alpha_4 \text{KL}_{it} \\
& + \alpha_5 \text{rKL}_{it} + \alpha_6 \text{KL}_{it}^2 + \alpha_7 \text{wage}_{it} + \alpha_8 \text{wage}_{it}^2 + \alpha_9 \text{rwage}_{it} + \alpha_{10} \text{revenue}_{it} \\
& + \alpha_{11} \text{water}_{it} + \alpha_{12} \text{purify}_{it} + \alpha_{13} \text{rwater}_{it} + \epsilon_{it}
\end{aligned}
\tag{2}
$$

where i represents the firm, c is for city, j is for sector and t is for year. All variables are expressed in logs. agg_{cjt} in Eq. (1) is the agglomeration index in city c that the firms located in sector j in year t. E_{it} is the volume of polluted water produced by each firm in each year. productivity_{it} is the firm's productivity using the firm's total revenue divided by the total employees of each firm in each year. grad_{ct} is the number of graduates in city c that firm i locates in year t. FDI_{ct} is the annual foreign direct investment in city c that firm i locates in the year t. export_{it} is the export intensity using total export divided by total revenue. It is the index to show the share of exports in the total revenue of each firm i. The higher of the export intensity, the higher the export value in the total revenue of the firm. KL_{it} is the firm's capital–labor endowment ratio. It is measured by using the total assets of the firm divided by yearly average employees. This index is to show whether the firm is a capital-intensive or labor-intensive producer. The higher the ratio, the firm is more capital-intensive. Otherwise, the firm is more labor-intensive. rKL_{it} is the relative capital–labor ratio to the national average level. rKL_{it} is calculated using the firm-level capital-intensive ratio which is KL_{it} divided by China's average capital-intensive ratio. wage_{it} is the

yearly average wage of the specific firm. wage_{it} is calculated using the total roll payment of the firm divided by the yearly average employees. rwage_{it} is the relative wage rate to China's national average rate. rwage_{it} is measured by the firm's average rate, which is wage_{it} divided by the national average rate. empl_{it} is the average number of employees of a firm i in the year t. empl_{it} is the yearly average number of employees. revenue_{it} is the yearly total revenue of the specific firm. water_{it} is the total volume of clean water used for the specific firm's production. purify_{it} is the measurement to show the number of purifying equipment the firm has to resolve the polluted water. rwater_{it} is the relative water usage to China's national average water usage. rwater_{it} is calculated by using the firm's water usage each year, which is water_{it} divided by the national average water usage in the industrial production sector. The higher of rwater_{it} means the higher of water input for production comparing to the national average level.

productivity_{it} is the variable of interest in our empirical model. We use this labor productivity to show the heterogeneous firms. It is the key variable in our model to extend trade and environmental study to the heterogeneous firm level. It is also an important indicator to test our PRR hypothesis. In this case, we are able to investigate the effect of productivity on water pollution in terms of the firm's exports. However, we have to admit that labor productivity is not a perfect option to be the proxy of heterogeneous firms. Alternatively, we can get total factor productivity (TFP) with a certain limited year range from 2000 to 2007. If we use labor productivity, we can cover all the years in the dataset from 2000 to 2012. Hence, we need to balance whether we should drop the year coverage to get TFP. OECD (2001) released a report on productivity measurements. We use labor productivity as the proxy of a firm's productivity, which is suggested by this report.

agg_{cjt} is the agglomeration of the firms. We use manufacturing agglomeration to measure whether agglomeration can play a role in water pollution. Our mechanism is that agglomeration can boost productivity increase. Hence, we want to test whether higher productive firm's water pollution is decreased by agglomeration. If it is so, our result on the mechanism of a firm's productivity and water pollution is robust. We follow studies by Cheng (2016) and O'Donoghue and Gleave (2004) to formulate agglomeration economies. It is measured based on the employment of firms as follows:

$$
\text{agg}_{cjt}(i) = \frac{L_{cjt(i)}/\sum_c L_{cjt}(i)}{\sum_j L_{cjt}(i)/\sum_c \sum_j L_{cjt}(i)}
\tag{3}
$$

Where L represents the number of employees and c represents city that firm i in sector j locates. The higher of $\text{agg}_{cjt}(i)$, the more agglomerated the city that the firm i locates for the specific industry. Since we use the number of firm's employees in the same industry to calculate agglomeration, we argue that $\text{agg}_{cjt}(i)$ is the proxy of intra-industry agglomeration. We also include squared agglomeration in Eq. (1). The reason to include squared agglomeration is that we need to coincide with the relationship between productivity and water pollution. We need to investigate whether the effect of agglomeration on the firm's productivity is straight linear or not. It fits our theoretical analysis to relate the competition effect and the firm's productivity changes.

export_{it} is the variable to estimate the export effect on the environment, which is water pollution in our paper. We use the total export value of the specific firm divided by the annual revenue of the firm as the proxy of the export effect. In traditional trade theory, comparative advantage can well explain the inter industry trade pattern. We can easily explain the effects of trade between dirty industry and clean industry. In terms of inter-industry trade, if China exports commodities from a dirty

industry and imports commodities from a clean industry, China's water pollution will increase.

However, when it comes to intra-industry trade, we need to understand the effect of trade in a specific dirty industry or clean industry. We are not sure whether the exported mode of commodities will produce more wastewater or less wastewater than the imported mode of commodities from the same industry. Whether a trade can make the water pollution of dirty industry or clean industry unchanged? Whether trade makes water pollution decrease totally? Unfortunately, we cannot solve this issue by using simply total export from one specific firm to all other countries due to data availability in the paper.

KL_{it} and rKL_{it} are used to estimate the composition effect. We follow the study by Cole and Elliott (2003). We use this variable to study the production factor mobility between dirty and clean firms. In the traditional trade theory, it usually assumes that the dirty sector is capital-intensive. It is necessary to have a factor ratio to show whether the firm is capital-intensive or not. We also want to include the relative capital-labor ratio of each firm to the national average level. Because comparative advantage is a concept and we have non-export firms in the model, we want to have a relative capital-labor ratio in the model to show the relative production factors to the national average level.

$wage_{it}$ and $rwage_{it}$ are used to estimate the technique effect. We follow the approach by Copeland and Taylor (2013) and Cole and Elliott (2003). Low-wage firms usually have a comparative advantage in dirty goods because of the low environmental production standards.

We follow the Kuznets curve literature and have the squared composition effect and squared technique effect, which are represented by KL_{it}^2 and $wage_{it}^2$. Since there is a strong inverted U-shaped relationship between per capita income and pollution according to the Kuznets curve, we need consider the effects in our model. The composition effect is represented by a country's capital-labor ratio. According to Cole and Elliott (2003), the square of the capital-labor ratio is included to allow capital accumulation to have a diminishing effect at the margin.

$revenue_{it}$ is to represent the scale effect. We need to know whether the increase in water pollution would be generated by scaled-up production and holding production techniques. Moreover, we not only focus on water pollution in our model but also need to consider the water input as the intermediate input. We also need to consider the equipment that is used to purify polluted water. The purified equipment can be a measurement of pollution abatement activities.

Data source. We combine three different datasets to construct our panel dataset. Our data are sourced from China's Annual Survey of Industrial Firms (ASIF), Annual Environmental Survey of Polluting Firms (AESPF), and China Statistical Yearbook (CSY). ASIF is a survey dataset conducted by China's National Bureau of Statistics. The survey is to investigate the manufacturing firms with a yearly income of more than 5 million Yuan. AESPF is a survey dataset conducted by China's Ministry of Ecology and Environment. ASIF includes all the economic-related indicators. AESPF includes environmental-related indicators. We merge these two datasets according to the firm's name and year.

The data source for all the economic-related variables is from ASIF, while the data source of all environments related is from AESPF. All the national-level data are from CSY. The time range of the datasets covers from 2000 to 2012. This is the most recent data we can get at the firm level.

Econometric approach. For the estimation technique, the existing literature uses OLS, fixed effect, or GMM approaches for

Table 1 Baseline estimations using 3SLS.

	(1) Productivity	(2) E_{ij}
Productivity		0.1405*** (0.0371)
Productivity2		−0.0162*** (0.0034)
Agglomeration	0.0139*** (0.0025)	
Agglomeration^2	−0.0214*** (0.0048)	
KL	0.3317*** (0.0048)	0.0589** (0.0277)
KL^2		−0.0147*** (0.0021)
rKL		0.0046 (0.0218)
Wage	0.5420*** (0.0099)	0.1233*** (0.0300)
Wage^2		−0.0302*** (0.0056)
rWage	–	
Export	−0.0336*** (0.0034)	0.0227*** (0.0040)
Water		0.7319*** (0.0130)
rWater		−0.0468*** (0.0125)
Purify		0.1874*** (0.0046)
Revenue		0.0319*** (0.0068)
Graduates	−0.0465*** (0.0050)	
FDI	0.0586*** (0.0042)	
Employees	−0.1141*** (0.0046)	
Constant	3.1869*** (0.1431)	
Year effect	Yes	Yes
Sector effect	Yes	Yes
Observations	20,200	20,200
R-squared	0.5802	0.8237

Standard errors in parentheses, ***$p < 0.01$; **$p < 0.05$.

estimation. In our empirical model, we have an ordinary panel dataset at the firm level covering 13 years. We use three-stage least squares (3SLS). In this paper, we investigate the effect of trade on the reallocation of production resources among heterogeneous firms and water pollution. In the empirical model, we study the agglomeration effect on a firm's productivity first and then heterogeneous firm's trade performance on water pollution. Therefore, we establish structural equations. The first equation's dependent variable is the second equation's independent variable. The structural equations create obvious endogenous issues, so we use 3SLS to solve endogeneity. Moreover, in the mechanism analysis and extensive discussion section, we use a fixed effect model because of the panel data.

Results and discussions

In the first column of Table 1, it is the estimated results of Eq. (1) using 3SLS. Intra-industry agglomeration is statistically significant and shows a positive sign. The squared agglomeration is also statistically significant but shows a negative sign. The two different signs above indicate that agglomeration of the firm's industry in the firm's city plays an inverted U-shaped effect on firm's labor productivity. Intra-industrial agglomeration firstly has a positive effect on productivity and then has a negative effect on productivity.

We argue that intra-industry agglomeration provides the driver for a firm's productivity change. Our estimation result proves that intra-industry agglomeration firstly drives productivity increase for both clean and dirty firms. When intra-industry agglomeration achieves a certain level, the effect of intra-industry agglomeration on a firm's productivity will decrease. Since we expect that firms are divided into high and low levels according to the firm's productivity, productivity drives the reallocation of production resources among firms in the same industry. That is why we need to continue to analyze Eq. (2), which is about the firm's productivity and water pollution.

In the second column of Table 1, it is the estimated results of Eq. (2). We get the benchmark estimation results for the firm's productivity and water pollution using 3SLS. The firm's labor productivity (Productivity) is statistically significant and has a positive sign. The squared Productivity is also statistically significant but shows a negative sign. The two different signs above indicate that a firm's labor productivity has an inverted U-shaped effect on water pollution. A firm's labor productivity firstly has a positive effect on water pollution. A firm's labor productivity later has a negative effect on water pollution. The effect of a heterogeneous firm's productivity on the firm's water pollution can increase the firm's water pollution and then decrease the firm's water pollution when the firm's productivity achieves a certain level. Hence, higher productive firms actually produce less polluted water when firm's productivity achieves a certain level in China. Therefore, we can argue that PRR does exist in the case of China's water pollution. We will continue to investigate the mechanism in the following section.

In the second column of Table 1, the capital–labor ratio (KL) is statistically significant and has a positive sign. The squared KL is statistically significant and shows a negative sign. However, the relative KL of the specific firm to the national average level is not statistically significant with year effect and sector effect. When the firm's capital–labor ratio achieves a certain level, the firm will produce less polluted water. Therefore, it means if a firm is more capital intensive, there will partially be less water polluted for the right side of the inverted U-shaped effect. Usually, in the traditional trade and environment theory, it is assumed that the capital-intensive sector is also the polluting sector (Copeland and Taylor, 2013).

The firm's average wage (Wage) is statistically significant and shows a positive sign. It indicates that if a firm offers a higher average wage for employees, the more polluted water the firm produces. The relative average wage to the national average wage (rWage) is dropped with year effect and sector effect. The squared wage rate (Wage²) is statistically significant and has a negative sign. It indicates that water pollution also shows a strong inverted U-shaped relationship with wage rate.

The firm's export intensity (Export) is statistically significant and has a positive sign. It means that the higher the export share in the total revenue of a firm, the higher polluted water will be produced. It is not difficult to demonstrate that more export actually needs more production which produces more polluted water. The firm's water usage (Water) is statistically significant and shows a positive sign. It means that the more water the firm uses, the more polluted water the firm produces. The firm's volume of water usage relative to the national average (RWater) is statistically significant and has a negative sign on the water pollution. It means the higher of relative water usage ratio of a firm to the national average level, the less polluted water the firm produces. If a firm uses more water for production relative to the national average level, the firm actually produces less polluted water. We believe that is because the more relative water the firm uses, the larger size of the production is. Firm's productivity is higher than the national average level, so water pollution is less relatively. The firm's capacity to resolve polluted water (Purify) is statistically significant and has a positive sign. It means that the higher the capacity of resolving polluted water equipped by the firm, the more polluted water will be produced. The interpretation is that if the firm has a higher capacity to purify the polluted water, it has less cost burden to produce more polluted water.

The firm's revenue is statistically significant and shows a positive sign. It means the higher of total revenue for the firm (Revenue), the more polluted water will be produced. It is not difficult to understand that higher total revenue means more production, and more production means more polluted water. At the firm level, revenue is considered to be the proxy of the scale effect. It means the more the firm earns, the more polluted water there will be. Scale effect always produces a positive effect, since more production is always with more water pollution.

We use the following equation to estimate interaction effects for productivity with export effect, composition effect, and technique effect:

$$\begin{aligned} E_{it} = \alpha_0 &+ \alpha_1 c.\text{productivity}_{it}\#\#c.\text{export}_{it} \\ &+ \alpha_2 c.\text{productivity}_{it}\#\#c.\text{KL}_{it} \\ &+ \alpha_3 c.\text{productivity}_{it}\#\#c.\text{Wage}_{it} \\ &+ \text{CNTR} + \epsilon_{it} \end{aligned} \quad (4)$$

where CNTR is the set of control variables which is the same as that in Eq. (2), including productivity²$_{it}$, KL²$_{it}$, wage²$_{it}$, rwage$_{it}$, revenue$_{it}$, water$_{it}$, purify$_{it}$, rwater$_{it}$.

Table 2 is the interaction test of export effect (Export), composition effect (KL), and technique effect (Wage) with the firm's productivity using fixed effect. The reason to use fixed effect instead of 3SLS to have an interaction test is that we need to prove the theoretical mechanism using the second stage of our empirical model. We have already finished the basic analysis to link intra-industry agglomeration, productivity, and pollution using 3SLS via two equations. At this stage, we do not need two equations to test the interaction effect and prove the effect of trade on water pollution. That is why we use fixed effect in the discussion section.

The interaction term of a firm's labor productivity and export intensity is statistically significant and has a positive sign. It means that the export effect on water pollution is increased through labor productivity. The export effect on water pollution is conditional on the value of productivity. We can also conclude that the export effect on water pollution can be enhanced by a firm's productivity. The positive sign of interaction term for export effect and productivity implies that exporting enhances a firm's water pollution through productivity or is conditional on the value of productivity. Export effect dominates at the stage when the firm's productivity is relatively low. Hence, we can conclude that when a firm's productivity is low, the export effect dominates.

The interaction term of a firm's labor productivity and a firm's capital–labor ratio is statistically significant and has a negative sign in Table 2. The composition effect on water pollution can be weakened by a firm's productivity. The composition effect on water pollution is conditional on the value of productivity. Alternatively, we can conclude that firms can increase capital-intensive production with less water pollution by increasing the firm's productivity.

Table 2 Interaction of productivity with "three effects".

	(1)
	E_{ij}
c.Productivity#c.Export	0.0156*** (0.0056)
c.Productivity#c.KL	−0.0229* (0.0121)
c.Productivity #c.Wage	0.2312*** (0.0718)
CNTR	−
Year effect	Yes
Sector effect	Yes
Observations	20,930
Number of i.d.	13,184
R-squared	0.5094

Export represents the export effect; KL represents the composition effect; Wage represents the technique effect. Standard errors in parentheses, ***$p < 0.01$, *$p < 0.1$; CNTR is control variables. The same applies to the rest tables.

Table 3 Interaction of employees with export effect.	
	(1)
	Size
c.Employees#c.Export	−0.0149** (0.0060)
	−
CNTR	CNTR
Year effect	Year effect
Sector effect	Sector effect
Observations	20,930
Number of i.d.	13,184
R-squared	0.5085
Standard errors in parentheses, **p < 0.05.	

The interaction term of firm's labor productivity and firm's average wage is statistically significant and has a positive sign in Table 2. The technique's effect on water pollution can be enhanced by a firm's productivity. The technique's effect on water pollution is conditional on the value of productivity. Alternatively, we can conclude that when the firm increases the wage rate, more water pollution will be produced by increasing the firm's productivity. A firm's labor productivity can strengthen the technique's effect on water pollution through wage rate.

Based on the estimation results of Tables 1 and 2, when we fix other variables, we can observe that export intensity is statistically significant and has a positive sign. Moreover, when we take the interaction test with productivity and export intensity, we find that the interaction term becomes statistically and positively significant. We can confirm that actually export intensity indeed has a strong relationship with productivity and contributes to the effect of the firm's water pollution.

However, we still do not know how trade reallocates production resources and results in the production rationalization effect with productivity. Hence, we need more analysis on the allocation of production resources, which is labor in our case. We introduce the interaction model of the firm's employees and export intensity to check whether the production resources, such as labor, would be reallocated due to export activities. To validate the labor production factor reallocation with the effect of exporting, we take the interactive test for the firm's employees and export intensity as follows:

$$E_{it} = \alpha_0 + \alpha_1 c.\, \text{Employess}_{it} \#\# c.\, \text{export}_{it} + \text{CNTR} + \epsilon_{it} \quad (5)$$

where CNTR is the set of control variables, which is the same as that in Eq. (2). In Table 3, the interaction term of the firm's employees and the firm's export intensity is statistically significant and has a negative sign. It means that the effect of a change in employees on water pollution depends on the value of the conditional variable firm's export intensity. It implies firm's number of employees weakens water pollution through export activity. Each additional unit of employees decreases the effect of export intensity on water pollution. We argue that this could be because of the usage of labor-saving technology.

The result complies with our theoretical implications that water pollution can be decreased by trade via the reallocation of labor from dirty firms to clean firms. In this case, size effect dominates with the channel of trade. Therefore, we can conclude that the production factor, which is labor is an important mobile reallocated resource among firms with different productivity levels.

However, we cannot ignore the different signs of the two interaction terms in Tables 2 and 3. The coefficient of interaction test of productivity and export effect (Export) in Table 2 is

statistically significant and shows a positive sign. The coefficient of interaction test of employees and export effect (Export) in Table 3 is statistically significant and shows a negative sign. From the first interaction test in Table 2, we conclude that the export effect enhances water pollution through the firm's productivity. From the second interaction test in Table 3, we conclude that the export effect weakens water pollution through the firm's employee size. Hence, different channels for export effects to impact water pollution may drive different results.

At this point, we need to relate the negative coefficient of interaction terms of the firm's labor productivity and the firm's capital–labor ratio in Table 2. It shows that the composition effect weakens water pollution depending on the conditional value of the firm's productivity. Therefore, we believe that the firm's employee changes will induce the composition effect. In a word, the positive sign of the interaction term of productivity and export effect (Export)implies that the export effect dominates, while the negative effect of the interaction term for productivity and capital–labor ratio implies that the composition effect dominates.

However, we cannot ignore the positive effect of scale effect coming from the increase in a firm's production or revenue. The scale effect can be estimated with the firm's revenue in our case. The firm's revenue is the sum of export sales and domestic sales. We believe that the reallocation of labor is a channel for firms to transfer production and change production as well as revenue. Hence, the water pollution reduction from the reallocation of labor overwhelms the positive scale effect. This can be supported by Cherniwchan et al. (2017), that trade liberalization lowers industrial emissions and the effect of emission reduction is larger than the pollution increments from the positive scale effect.

After we analyze the implications above, it seems that the mechanism is ambiguous and not straightforward enough, especially when it refers to the interaction models. We can find that the effect of a firm's productivity on water pollution is conditional on the value of exports. It will be substantively meaningful if we can find changes in the effect. This change can also help better understand the inverted U-shaped relationship between productivity and water pollution. Therefore, in the following section, we use the marginal effect to further identify the effect of productivity on water pollution with the conditional values of other channels.

In Fig. 1, when we use the firm's productivity as a conditional variable, we can see that the marginal effect of export intensity on water pollution is negative as firm's productivity is smaller than log value of productivity 6.2 which is the red line shown in the figure. However, it becomes positive, when firm's productivity is larger than 6.2.

Figure 1 shows that the export effect can indeed have a partial marginal effect to increase water pollution and a partial marginal effect to decrease water pollution on the conditional value of a firm's productivity. Therefore, this validates the different effects of productivity on water pollution at different stages.

In Fig. 2, when we use the firm's employees as a conditional variable, we can see that the marginal effect of the firm's export on water pollution is decreasing until the log value of export intensity is 4.7, which is the red line shown in the figure. Figure 2 shows that a unit increase of employees will have a decreasing marginal effect on the firm's water pollution on the conditional value of export intensity. Vice versa, a unit decrease of employees will have an increasing marginal effect on the firm's water pollution if the log value of export intensity is smaller than 4.7. However, when a firm's export is large enough, the effect of employees on water pollution does not depend on export anymore.
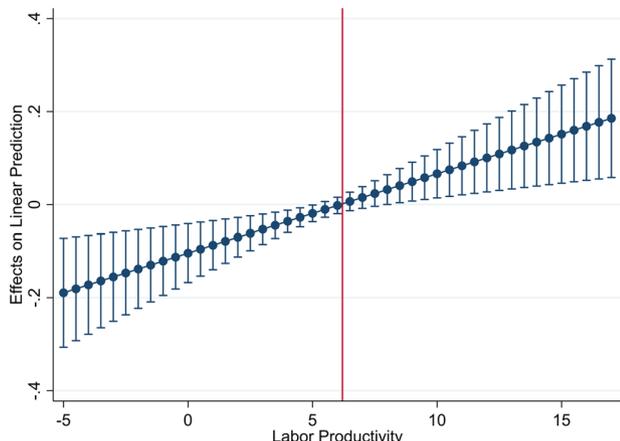
Fig. 1 Average marginal effects of export intensity with different levels of productivity. Displays the average marginal effects of export intensity with different levels of productivity. It mainly shows the conditional value of a firm's productivity for the effect of export intensity on water pollution. The red line is the firm's productivity and is equal to 6.2 in log value. Based on the author's own calculation.
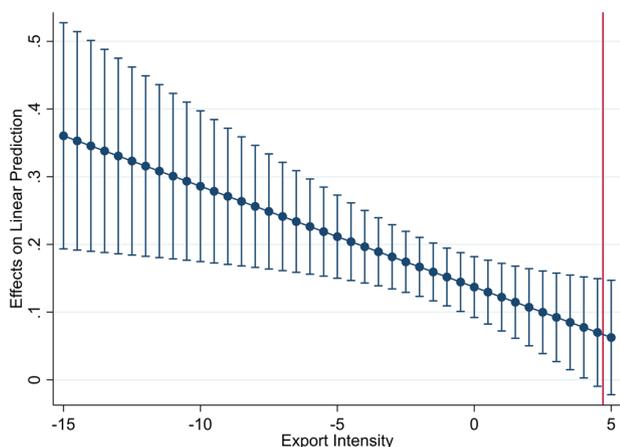

Fig. 2 Average marginal effects of export intensity with different levels of employees. Displays the average marginal effects of export intensity with different levels of employees. It mainly shows the conditional value of the firm's employees for the effect of export intensity on water pollution. The red line is export intensity and is equal to 4.7 in log value. Based on the author's own calculation.

Our analysis above shows validation of the relationship between a firm's productivity, export and labor reallocation through interaction model and marginal effect. As stated in PRR, more productive firms export and export, which makes dirty firms exit and the production resources from dirty firms will be reallocated to clean firms.

Extensive discussions

As we discussed above, export actually decreases a firm's water pollution eventually. Export firms have higher productivity. High-productive firms pollute less water. We need to further investigate whether agglomeration and production resources can be reallocated between exporting firms and non-exporting firms.

We then move to export agglomeration. We want to test whether an exporting firm's agglomeration can play a role in a firm's water pollution. Instead of using the firm's manufacturing sector, we divide firms into the export sector and the non-export sector. We simply replace the sector j in Eq. (3) with x, which

represents the exporting sector. In this way, we are able to examine the effect of exporting agglomeration on the reallocation of a firm's production resources. We use the interaction term of exporting agglomeration and the firm's capital–labor ratio to show whether exporting firms can gain more production resources from non-exporting firms.

$$\text{agg}_{cxt}(i) = \frac{L_{cxt(i)}/\sum_c L_{cxt}(i)}{\sum_x L_{cxt}(i)/\sum_c \sum_x L_{cxt}(i)} \quad (6)$$

where x represents exporting sector, which is different from Eq. (3). If a firm exports in a specific year, the firm is in the exporting sector. The higher of $\text{agg}_{cxt}(i)$, the more exporting firms are agglomerated in city c that firm i locates. From the exporting sector perspective, we employ the following equation to test the interactive effect for the agglomerated exporting sector and the firm's capital–labor ratio.

$$E_{it} = \alpha_0 + \alpha_1 c.\text{Agg}_{cxt}\#\#c.\text{KL}_{it} + \text{CNTR} + \epsilon_{it} \quad (7)$$

Where CNTR is the set of control variables which is the same as that in Eq. (2). In Table 4, the interaction term of exporting agglomeration and the firm's capital-labor ratio is statistically significant and shows a positive sign. It indicates that exporting agglomerated firm's wastewater increases through the firm's capital–labor ratio. This is because firms' production resources will be reallocated to exporting firms. This result seems contradicts to our expectations in PRR. The question is whether it is a straight linear line effect or not. Therefore, we continue to test whether the effect is the same with the squared capital–labor ratio.

Following the estimation result from Table 4, we need to validate whether the effect of exporting agglomeration and the firm's capital-labor ratio is straight linear. In this case, we need to include the interaction term of exporting agglomeration and squared KL. If the signs of coefficients of two interactive terms are different, it will imply that the effect is not straight linear and we can relate the different signs of coefficients with our analysis on production resources reallocation. Therefore, we use the following estimation equation:

$$E_{it} = \alpha_0 + \alpha_1 c.\text{Agg}_{cxt}\#\#c.\text{KL}_{it} + \alpha_2 c.\text{Agg}_{cxt}\#\#c.\text{KL}_{it}^2 + \text{CNTR} + \epsilon_{it} \quad (8)$$

Where CNTR is the set of control variables, which is the same as that in Eq. (2). Table 5 reports the interaction terms of exporting agglomeration with the firm's capital–labor ratio and the squared ratio. The interaction term of exporting agglomeration with the firm's capital–labor ratio is now statistically significant but shows a negative sign, which is different from Table 4. However, the interaction term of exporting agglomeration with the firm's squared capital–labor ratio is statistically significant but shows a positive sign. It indicates that the effects of KL and squared KL on

Table 4 Exporting agglomeration, capital–labor ratio and water pollution.

	E_{ij}
c.Agg_export#c.KL	0.0584** (0.0278)
CNTR	–
Year effect	Yes
Sector effect	Yes
Observations	20,930
Number of i.d.	13,184
R-squared	0.5084

Standard errors in parentheses, **$p < 0.05$.

Table 5 Exporting agglomeration, resources reallocation and water pollution.

	E_{ij}
c.Agg_export#c.KL	−0.1416* (0.0776)
c.Agg_export#c.KL2	0.0257*** (0.0093)
CNTR	--
Year Effect	Yes
Sector Effect	Yes
Observations	20,930
Number of i.d.	13,184
R-squared	0.5089

Standard errors in parentheses, ***$p < 0.01$, *$p < 0.1$.

Table 6 Regional effect on the flows of labor in tradable sectors.

	Region
East	0.0383* (0.0222)
Northeast	−0.0008 (0.0355)
Center	–
West	−0.0673** (0.0289)
CNTR	–
Year effect	Yes
Sector effect	Yes
Observations	20,200
R-squared	0.8239

Standard errors in parentheses, **$p < 0.05$, *$p < 0.1$.

water pollution are conditional on exporting agglomeration levels but with different signs.

The different signs for the firm's capital–labor ratio and squared capital–labor ratio indicate that more agglomerated exporting firms in the city do not always increase the firm's wastewater by gaining resources from non-exporting firms. The exporting agglomeration in the city has also decreased the firm's wastewater by gaining resources from non-exporting firms after certain agglomeration level. The reason is that competition affects sourcing from different levels of exporting agglomeration among firms in exporting sector increases exporting firm's productivity. Hence, this mechanism also proves PRR.

The exporting agglomeration above provides a clear relation analysis between exporting agglomeration and production resources allocation. We confirm that high-productivity firms export, resulting in less water pollution since export is relevant to productivity and water pollution.

Exporting activities in China have very diverse geographic disparities. Usually, we can observe that the eastern area is the exporting gateway for China. Hence, we want to investigate water pollution in different regions in China.

Table 6 shows the estimated results for different regions in China. It shows different regional characteristics of water pollution. We can find that firms located in the eastern area are more likely to pollute more water. While firms located in the western area are more likely to pollute less water.

Conclusions and policy implications

In this paper, we study Pollution Reduction by Rationalization Hypothesis on water pollution using Chinese firm-level data. We investigate heterogeneous firm's export effect on water pollution. We find that the relationship between a firm's labor productivity and water pollution is inverted U-shaped. With heterogeneous firms, we find that

more productive firms can export with less polluted water when a firm's productivity achieves a certain level. We conclude that export makes firms cleaner in terms of water. Agglomeration drives up labor productivity; higher productive firms export while producing more polluted water initially. When a firm's productivity is high enough and achieves a certain level, exporting activity produces less polluted water. We first provide such an inverted U-shaped relationship in the benchmark estimation. Then, the two interaction models of the firm's productivity and export intensity, as well as the firm's employees and export intensity, prove the relationship of labor mobility among different firms. The marginal effect of export intensity also identifies that the export effect on water pollution is conditional on the firm's productivity. The mechanism of the PRR hypothesis does exist. Trade liberalization does cause some firms to become cleaner, even though we observe relatively clean exporting firms and relatively dirty domestic producers at different productivity stages. Export causes water pollution to fall with high firm productivity, because of productivity-induced rationalization. Therefore, our empirical study on China's water pollution validates the PRR hypothesis. More productive firms can export with less polluted water by reallocating more productive labor from dirty firms. The reallocation of production factors affects water pollution through trade.

Moreover, composition effect and technique effect also play roles in the firm's water pollution in China. In terms of composition effect, firms can increase capital-intensive production with less water pollution by increasing the firm's productivity. In terms of technique effect, labor productivity can strengthen the technique effect on water pollution through relative wage rate.

Our study has a clear policy implication. In China's water resources management system, China should concentrate on productivity enhancement and encourage export with restrictions on water pollution. Policy can favor productive firm's water pollution abatement. The first basic policy is to continue to export, since exporting does not necessarily increase wastewater in China. The second policy is to make use of industry policy to connect sectoral agglomeration policy as well as water protection policy with exporting policy. Water protection policy can be efficient by enhancing sectoral agglomeration and exporting.

A potential future research direction can be in line with intra-industry trade. If possible, it is valuable to investigate the intra-industry trade at the firm level with pollution if all the import-related data from a specific country are available. Another possible research direction can be related to green technology innovation. It is also promising to combine patent datasets to investigate the effect of green technology innovation on the reduction of wastewater as well as the spillover effect on the reduction of wastewater in the same or neighboring geographic area. We also encourage researchers to investigate the distressed and dirty industry hypothesis and pollution offshoring hypothesis for different pollutants.

Data availability

The datasets generated and analyzed during the current study are not publicly available due to that ASIF and AESPF were used under licence for the current study, and so are not publicly available, but are available from the corresponding author on reasonable request.

Note

1 https://www.worldbank.org/en/news/press-release/2018/11/07/china-a-watershed-moment-for-water-governance

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Author contributions

The author confirms sole responsibility for the following: study conception and design, data collection, analysis and interpretation and discussions of results, and manuscript preparation.

Competing interests

The author declares no competing interests.

Ethical approval

This article does not contain any studies with human participants performed by any of the authors.

Informed consent

This article does not contain any studies with human participants performed by any of the authors.

Additional information

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