Environmental Science and Policy 96 (2019) 132–140

Contents lists available at ScienceDirect

Environmental Science and Policy

journal homepage: www.elsevier.com/locate/envsci

What can we learn about effectiveness of carbon reduction policies from interannual variability of fossil fuel CO_2 emissions in East Asia?

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ARTICLE INFO

Keywords:
East Asia
Carbon emissions
Carbon abatement

ABSTRACT

Although most countries have submitted their Nationally Determined Contributions (NDC), there is a lack of understanding what policies are effective in terms of carbon emission reduction under the announced pledges. We use East Asia as a case study to estimate the importance of national environmental policies in terms of reduction in fossil fuel carbon emissions ($FFCO_2$). We show that the flagship policies of China, Japan, South Korea and Mongolia in the 2010s were generally beneficial in terms of slowing down $FFCO_2$ growth rates. When flagship polices were enacted, annual $FFCO_2$ growth rate has either slowed down by 1% (South Korea), 5% (Mongolia), 8% (China) or even resulted in a decline (Japan) comparing to prior periods. We find that the 12th Five-Year Plan (12th FYP) of China had the strongest footprint in $FFCO_2$ emission dynamics across East Asia in 2010s. The recent slowest rate of $FFCO_2$ growth across East Asia (2011–2015) temporally corresponds to the 12th FYP. This regional pattern of $FFCO_2$ dynamics is driven by decrements in annual growth of $FFCO_2$, coal use and cement production of China (all ˜8% per yer decrease) during the 12th FYP. Using compound periodical growth of $FFCO_2$ emissions, we provide two baseline projections of emission distribution in East Asia, by assuming that all policies are enacted (policy-on) or not (policy-off) in the future. The projections show that policies were beneficial since policy-on scenario results in 24%, 80%, 166% less $FFCO_2$ emissions than in policy-off scenario in East Asia by 2020, 2025 and 2030 respectively. This progress is yet insufficient for reaching NDC goals by 2030. Even in policy-on scenario in 2030, East Asian countries would either experience insufficient decline of $FFCO_2$ like Japan (-13% of $FFCO_2$ comparing to pledged -17%) or increase of $FFCO_2$ like South Korea (11%) and Mongolia (4%) comparing to 2010 level. For China, due to lack of economy-independent goals, we were unable to assess NDC target compliance. We demonstrate that China will remain as the major $FFCO_2$ emitter of EA in near future in any projection. For China, the highest emission cluster will remain at the Eastern Provinces with the strongest power generation demand. These provinces would be responsible for 43% and 52% of $FFCO_2$ emissions in East Asia in policy-off and policy-on scenarios. We concluded that the current efforts of national flagship environmental policies are beneficial but not sufficient for reaching ambitious carbon reduction goals like Paris Agreement. This study once again underlined the necessity in the supranational framework that may control the carbon abatement goals in East Asia. Without the supranational framework, achievements in carbon emission reductions are strongly hindered by the socioeconomic environment and the regional (or sectoral) emphasis of carbon reduction activities within a national economy.

1. Introduction

There is a concern that many nations are unable to reach the Paris Agreement goals due to insufficient reduction of carbon emissions and greenhouse gases (CAT, 2018). The effectiveness in reducing carbon emissions by national governments is hindered by two factors such as necessity to sustain a balance between economic growth and carbon abatement activities and the lack of coordination between domestic policies and international pledges like Paris Agreement (Benveniste et al., 2018). Instead of well-coordinated carbon reduction action, a

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https://doi.org/10.1016/j.envsci.2019.03.011
Received 22 November 2018; Received in revised form 1 February 2019; Accepted 19 March 2019

Table 1
Environmental policies in EA during 2010–2017 period. The 12th Five-Year Plan of China (or 12th FYP), Innovative Strategy for Energy and Environment of Japan (ISEE) Energy Target Management System of South Korea (TMS) and 1st stage of National Action Programme on climate change of Mongolia (1st NAP). *ISEE was considered to be working policy tool for carbon reduction in Japan until 2020/2030 but ISEE was canceled in 2016.

Policy	Country	Start Year	End Year	Pledge (% decrease)
12th FYP	China	2011	2015	− 17% of carbon emission intensity (nationwide) − 10-18% of carbon emission intensity (in provinces)
ISEE*	Japan	2013	2020/2030 (planned) 2017 (considered)	- In 2020, decrease GHG emissions by 5-9% vs 1990 level - In 2030, decrease GHG emissions by 20% vs 1990 level
TMS	South Korea	2012	2020	- within 30% of GHG emission from business-as-usual scenario
1st NAP	Mongolia	2011	2015	- GHG emission mitigation (technological improvements)

diversity of policy instruments and tools was applied to tackle carbon emissions at national scales. The lack of aforementioned coordination propels the question on how effective are the current environmental policies for decreasing carbon emissions within a single nation.

From this perspective, East Asia (EA) perhaps is the most prominent region worldwide. EA is a key player in the world of global change being responsible for nearly 33% of $FFCO_2$ emissions (Le Quéré et al., 2017). The diversity of policy approaches towards $FFCO_2$ reduction is peculiarly high in EA due to unique socioeconomic challenges and the heritage of geopolitical conflicts within the region. Some nationwide carbon reduction plans in EA have proved efficiency, while other policies barely influenced $FFCO_2$ emissions. For instance, the progress of carbon-reduction initiatives of 2000s in EA was questioned, as China CO_2 emissions were growing at alarming annual rate of 7.4–8.0% at that time (Zhao et al., 2013). To avoid inefficient use of police power in the future, many optimal pathways for decreasing $FFCO_2$ (and greenhouse gases) have been proposed for EA (Oshiro et al., 2016), (Jin et al., 2017), (Liu et al., 2018). Nevertheless, the efficiency of current policy tools for reaching $FFCO_2$ decrease is more obscure. For many years, quantitative evaluation of environmental policies has been hindered in EA due to sparse regional cover by ground-based CO_2 measurements. Sparse cover limits CO_2 observational network (Tang et al., 2018), and reduces potential of regional inverse modelling (Peylin et al., 2013). The use of energy national statistics for CO_2 accounting is common in EA but yet suffers from unknown quality of data from developing economies (Gregg et al., 2008), (Guan et al., 2012). Moreover, when national energy statistics approach is adopted, Tibet and Taiwan (Meng et al., 2011), (Guo et al., 2012), (Feng et al., 2013), (Deng et al., 2015) are often not analyzed due to inconsistency in regional data collection. In addition to these constraints, there is a deficiency of supra-national analysis of $FFCO_2$ dynamics in EA. In particular, most scholars investigated $FFCO_2$ emission dynamics and distribution in strictly national scales within EA (Gregg et al., 2008), (Kim et al., 2010), (Meng et al., 2011), (Zhao et al., 2012), (Makido et al., 2012), (Deng et al., 2015) and policy-relevant research is often focused at one country (Zheng et al., 2018).

To understand the effectiveness of the current nationwide policy tools in reducing carbon emissions in EA, we set the main questions of this study as (a) What is the role of national environmental policies with carbon reduction goals in change of temporal dynamics of $FFCO_2$ in EA? (b) What are the most impactful policies in terms of slowing down $FFCO_2$ emissions in EA? (c) What are the future consequences of environmental policies in EA in terms of $FFCO_2$ reduction required by NDC? Our methodology is based on interannual variability (IAV) of $FFCO_2$ because we suggest that IAV signal of $FFCO_2$ is sensitive to anthropogenic activity. Even in IAV signal of atmospheric CO_2 fraction, significant portion of human activity (36%) can be traced (Buchwitz et al., 2018). We further analyze the effects of environmental policies in IAV signal of $FFCO_2$ emissions (of EA in 2010–2017 period) estimated using the state-of-the-art methodology from ODIAC (Open-source Data Inventory for Anthropogenic CO_2).

2. Review of environmental policies for CO_2 reduction in East Asia

EA consists of China, Democratic People’s Republic of Korea (North Korea), Japan, Mongolia and Republic of Korea (South Korea). In EA, most carbon reduction actions during the 2010s are formulated under the framework of national climate mitigation strategies or energy plans with climate implications (environmental policies from hereafter). This section is devoted to selection of the flagship national environmental policies aimed at $FFCO_2$ (or GHG) reduction in EA during 2010–2017 period. The great challenge stems from a wide variety of policies, plans, and frameworks have been issued since 2010 at national scales in EA. Moreover, NDC structu is flexible and there is no framework regulating national governments to follow specific format or satisfy certain numeric criteria in carbon reduction. In the NDC texts of EA countries, one may find references to environmental policies intended to be police power tools for NDC performance (China, South Korea and Mongolia). In other cases, NDCs do not imply what policy tools should control the execution of the pledge (Japan). A selection of the flagship national environmental policies in EA is briefly described here (detailed description is in supplementary material S1). We use a set of policies (Table 1) including 12th Five-Year Plan of China (2011–2015), Energy Target Management System of South Korea (2012…), Innovative Strategy for Energy and Environment of Japan (2013…) and 1st phase of National Action Program of climate change of Mongolia (2011–2015). For North Korea, there are no available documents about environmental policies and NDC pledges are set only since 2016 (lack of data for analysis). Each environmental policy of EA does not only feature distinct technical details, but also has different socioeconomic context of implementation.

For instance, the 12th FYP of China is a policy tool using vertical implementation of goal accomplishment from central to regional governments within very short period. Main features of 12th FYP are prioritizing economic restructuring over economic growth and shifting towards consumption-driven society in the socialism-oriented economy. Plan-based approaches for solving environmental challenges are sometimes referred as “environmental authoritarism” (Engels, 2018), that is seen as a distinct feature of China’s policies nowadays. Whilst $FFCO_2$ reductions goals of 12th FYP were clearly formulated (see Table 1), actions towards carbon abatement are inexplicit. As one of the strongest carbon emitters, Japan had formulated promising $FFCO_2$ reduction strategy that should have heavily relied on nuclear energy. However, “triple disaster” of 2011 urged Japan to give up betting on nuclear power and many policies were reconsidered. Japan environmental policies were influenced by the state energy plans. Consequently, the government role in such environmental plans of post-Fukushima Japan has enhanced (Kucharski and Unesaki, 2018). ISEE was formulated in such circumstances and enacted in 2013. Despite it had been initially planned to be operative until 2020/2030, the change of ruling party in Japan (in 2016) led to cancellation of this plan much ahead of the finishing line. It was replaced by Plan for Global Warming Countermeasures (2016…). We do not reject ISEE plan as a policy for Japan to see how the effects of drastically changed policies affect any $FFCO_2$ dynamics. We assume that IEEE was enacted 4 + 1 years (including 2017 when it was rejected). TMS is used as the environmental policy in 2010–2017 for South Korea. The distinct feature of this policy is a principle of implementations since it targets on firms rather than industrial sector. TMS relies on the mutual agreement between the government and firms that produces large amount of GHG or consumes large portion of energy. The approach is reasonable since many companies underachieve their $FFCO_2$ reduction goals (Goldstein et al., 2018). The South Korea government pursues reward and penalty approach towards GHG reduction for every firm, which the emphasis is given to waste production and electronic production sector. 1st NAP is a flagship policy for Mongolia and the least specified environmental policy where the first stage (2011–2015) is dedicated to strengthening of mitigation and adaptation capacities of the economy.

3. Data and methods

3.1. Fossil fuel CO_2 emissions

The estimates of $FFCO_2$ emissions are produced using ODIAC. ODIAC modelling framework accounts for emission estimates from energy use statistics and carbon component of fossil fuels. The CO_2 inventories include emissions from fossil fuel combustion, cement production and gas flaring. ODIAC features high spatial resolution and attribution of $FFCO_2$ emissions sources within urban areas and power plants (Oda et al., 2018). The information of urban areas is retrieved from DMSP/OLS (Defensive Meteorological Satellite Program/Operative Linescan Scanner) night-time lights imagery. We used the latest version of ODIAC (2018) product between 2000 and 2017 ($1 \times 1^\circ$ mean $FFCO_2$). Emissions estimates are obtained from the website of the National Institute of Meteorological Sciences of Japan (https://db.cger.nies.go.jp/dataset/ODIAC/).

3.2. Ancillary data

We also used IAV of cement production and coal consumption in EA (as carbon-rich processes). Cement production datasets were taken from the recently published data (Andrew, 2018). Coal consumption data were obtained from hard coal consumption (UN datasets from http://data.un.org).

3.3. Calculation of interannual growth of fossil fuel CO_2 emissions

IAV is the main parameter expressing year-to-year $FFCO_2$ emission dynamics. IAV of $FFCO_2$ is simply calculated as the difference between summed $FFCO_2$ of the regional unit (depending on the type of analysis) between the i^{th} year and $(i+1)^{th}$ year (Eq. 1.0). We do not use the difference between years in the plots for saving space (IAV_{2013} will stand for $FFCO2_{2013}$-$FFCO2_{2012}$ difference).

$$IAV\,(FFCO_2)_i = FFCO_{2(i)} - FFCO_{2(i-1)} \tag{1.0}$$

To quantify the difference in $FFCO_2$ growth rates between the periods when environmental policies are enacted (policy-on) with periods beforehand (policy-off), we apply compound periodical growth rate (CPG) of $FFCO_2$ for each large emitter of EA. CPG is used in economy statistics and has recently been proposed as a parameter to describe environmental phenomena in the growth stage (Sivaprasad, 2012). Since $FFCO_2$ exhibits primarily steady growth, we consider CPG as the appropriate parameter for our study. Our CPG formulation is based on Eq. 2.0 that shows the ratio between final values of annual $FFCO_2$ ($FFCO_{2f}$) and starting values of $FFCO_2$ ($FFCO_{2b}$) in specific time interval (n is the total number of years during the period of analysis). As mentioned, two different CPGs for policy-off and policy-on periods are applied. For instance, in China, policy-on period corresponds to 12th FYP enactment (2011–2015) and the policy-off period of China is 2000-2010. The policy-off and the policy-on periods of each emitter in EA differ according to the considered environmental policy within this emitter (see Table 1).

$$CPG = \left(\frac{FFCO_{2f}}{FFCO_{2b}}\right)^{\left(\frac{1}{n-1}\right)} - 1 \tag{2.0}$$

Using policy-off and policy-on CPGs, and by applying $FFCO_2$ estimates from last available year (2017) in our analysis, we draw two simple baseline projections for future $FFCO_2$ distribution across EA (in 2020, 2025 and 2030). We assume that policy-on CPG remains constant in the future until the year of final prognosis. This is a strict assumption but in this way we can comprehensively understand the effects of policy-on projection. In Equation 3.0, $FFCO_{2f}$ stands for the $FFCO_2$ summarized emissions quantified from last available year (2017) from ODIAC (2018 version), and $FFCO_{2p}$ stands for the projected summarized $FFCO_2$ emissions (2020, 2025 and 2030 in this study). In Eq. 3.0, n is the number of years between $FFCO_{2p}$ and $FFCO_{2f}$.

$$FFCO_{2p} = FFCO_{2f} * (1 + CPG)^{\Delta n} \tag{3.0}$$

4. Results

4.1. Fossil fuel CO_2 emission rate and interannual variability in East Asia

We introduce $FFCO_2$ dynamics across EA and outline the distinct periods of $FFCO_2$ growth during 2000s and 2010s. In Fig. 1 (left panel), we show that $FFCO_2$ is steadily growing in EA and the unchallenged emission leader of the region is China (79.2–90.1% of $FFCO_2$ from EA). Contrary to clear positive trend of summarized $FFCO_2$, IAV of $FFCO_2$ pattern exhibits several distinct periods in the 2000s and the 2010s. First period of the 2000s is related to intense growth of $FFCO_2$ emissions in 2000-2003. During the period of intense growth, IAV of $FCCO_2$ has mounted from 3.6% to 14.3% due to growing coal consumption (Fig. 1, right panel). Second period reveals lagging of $FFCO_2$ emission growth (2004–2009). We note that $FFCO_2$ emissions were growing during this period, but the growth was slowing down seven years in a row until reached IAV of 4.6% in 2009 (driven by decreased IAV of coal consumption since 2003 shown by black line in Fig. 1, right panel).

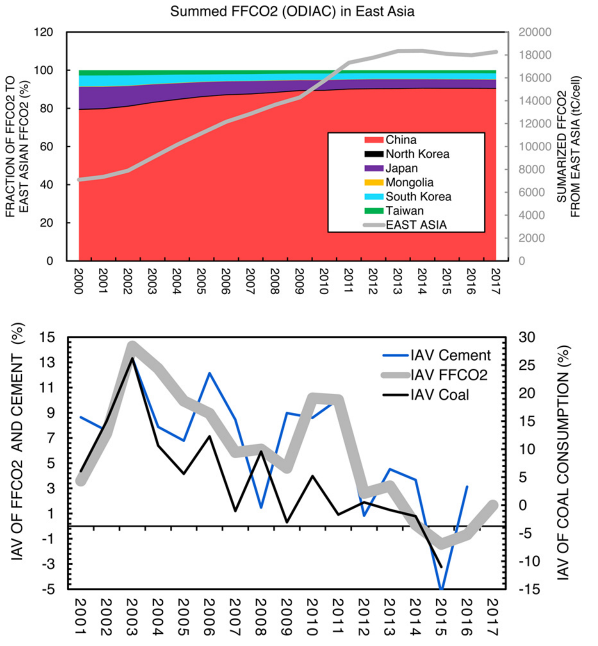

Fig. 1. Top panel: Summed $FFCO_2$ emissions in 2010–2017 period in EA (gray line) and contribution to total $FFCO_2$ emissions (%) of EA from Mainland China (red), Japan (purple), South Korea (blue), Taiwan (green), North Korea (black) and Mongolia (yellow). Bottom panel: IAV of $FFCO_2$ (bold gray line), cement production (blue) and coal (black) consumption in EA.

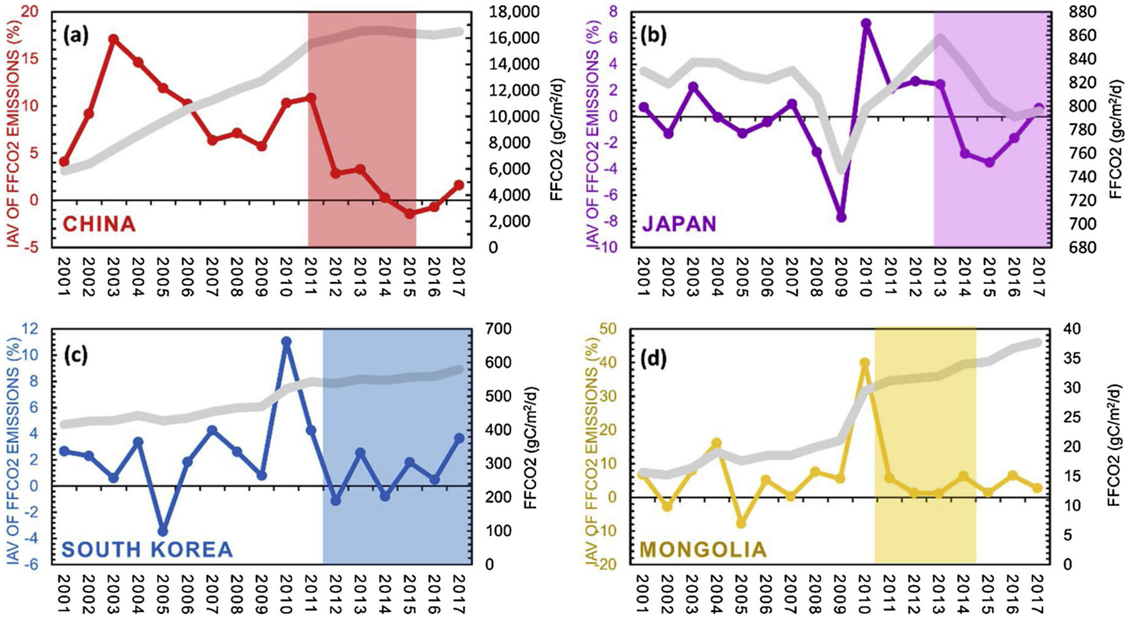

Fig. 2. $FFCO_2$ from ODIAC ($gC/m^2/d$) during 2000–2017 (gray bold line) and respective IAV of $FFCO_2$ in China (panel a, red), Japan (panel b, purple), South Korea (panel c, blue) and Mongolia (panel d, yellow).

Since 2009–2011 period, when IAV of $FFCO_2$ showed no dynamics, we observe two distinct periods in the 2010s. First period of 2010s is related to unprecedented decrease of $FFCO_2$ growth rate during 2010-2015: IAV of $FFCO_2$ has decreased from 10% in 2011 to -1.4% in 2015. The relative decrease in $FFCO_2$ was ended when the latest stage of $FFCO_2$ emission rebound during 2015-2017. We suggest that these patterns indicate the importance of carbon-liming effects in changing the pace of $FFCO_2$ growth since 2010.

We analyze IAV of $FFCO_2$ for four economies of EA during the policy-on periods (Fig. 2). For China, during the period of 12th FYP (2011–2015), IAV of $FFCO_2$ has decreased from 10.9% (2011) down to the observed minimum of -1.4% (2015). Lagged $FFCO_2$ growth in China during this period is driven by the well-known drop in national coal use (Korsbakken et al., 2016). The correlation coefficient between IAV of $FFCO_2$ and IAV of coal during this period is 0.76. After 12th FYP is finished, $FFCO_2$ growth has returned to growth stage in China and EA. For Japan, both $FFCO_2$ and IAV have complex patterns. The median IAV of $FFCO_2$ is ˜0 (the most invariant changes in $FFCO_2$ growth across EA in 2000–2017). The prominent period of $FFCO_2$ decrease corresponds to enactment of ISEE (2013) in Japan. During policy-on period of ISEE (2013–2017), Japan exhibited absolute minimum of IAV of $FFCO_2$ among other EA nations (3.5% decrease in 2015). Similar as China, Japan exhibited rebound in $FFCO_2$ emissions after 2016. For South Korea, the pattern of $FFCO_2$ growth is complex and IAV of $FFCO_2$ during TMS period varied only from -0.8 to 3.7%. This is the lowest variability of $FFCO_2$ growth among all EA countries during policy-on period. During policy-on period of 1st NAP (2011–2015), $FFCO_2$ variability in Mongolia was nearly constant and the role of 1st NAP is unclear.

4.2. Compound periodical growth of CO_2 emissions being compared between policy-off and policy-on periods

We calculate policy-off and policy-on CPGs for China, Japan, South Korea, Mongolia and Taiwan respectively. In Fig. 3, we illustrate CPGs for $FFCO_2$ (panel a) alongside with CPGs of cement production (panel b) and coal consumption (panel c). As seen, $FFCO_2$ growth has decreased in all large EA emitters when a national flagship policy was implemented during the period of study. We observe a decrease of CPG of $FFCO_2$ from 8.7% (policy-off) to 1.0% (policy-on) per year in China. Slowing of $FFCO_2$ growth rate is corresponded by lagged cement production growth as cement production CPG decreased from 9.1% (policy-off) to 0.7% (policy-on). Coal use CPG has similarly decreased from 7.3% (policy-off) to 0.8% (policy-on). We discover that CPGs of $FFCO_2$ in Taiwan have different trends comparing with China (CPG of policy-off is 3.1% and of policy-on period is -0.2% in Taiwan). Cement production of Taiwan differs from China as well since the production was decreasing in both policy-on (CPG = -1.2%) and policy-off periods (CPG = -2.7%). For Japan, weak $FFCO_2$ growth during policy-off period (CPG = 0.1% per year) has shifted to decrease in emissions (CPG = -0.3% per year). Coal use has similarly turned from weak growth (CPG = 0.1%) to decline (CPG = -0.8%). During both policy-off and policy-on periods, cement production was decreasing and their CPGs were equal to -2.4 and -0.3% per year respectively. For South Korea, we identify the weakest decrease of CPG from policy-off to policy-on period (decreased from 2.5% to 1.3% per year). Cement production and coal use have turned to growth in South Korea during policy-on period. For Mongolia, CPG of $FFCO_2$ has decreased from 6.6% (policy-off) to 2.0% (policy-on). Such decrease was corresponded by decline of cement production observed by CPGs of 11.2% (policy-off) and -0.5% (policy-on). We note that coal data for Mongolia and Taiwan was not available.

4.3. Two policy-dependent projections of CO_2 emissions in East Asia

We draw two baseline projections for 2020, 2025 and 2030 years (Eq. 3.0) using $FFCO_2$ of EA in 2017 and two different CPGs (policy-off and policy-on). For policy-off projection, total $FFCO_2$ across EA will exhibit 23 286, 35 365, 54 472 $gC/m^2/d$ by 2020, 2025 and 2030 respectively (24%, 80%, 166% increase comparing with 2017). For policy-on projection, total $FFCO_2$ are much lower and will be 18 753, 19 603, 20 509 $gC/m^2/d$ by 2020, 2025 and 2030 respectively (3%, 7%, 12% increase comparing with 2017). To understand the sensitivity of each region to the enactment of environmental policies, we calculate differences between $FFCO_2$ of two projections. From regional perspective, the role of the strongly-emitting cluster of EA (see yellow zone of Fig. 4) will increase in near future according to policy-off projection. Share of this cluster to total EA emissions will grow on 44%, 48%, 52% by 2020, 2025 and 2030 respectively. This highly emitting cluster is represented by the Eastern provinces of China with high power generation demand (Zhejiang, Jiangsu, Shandong, Hebei, Anhui, Henan).

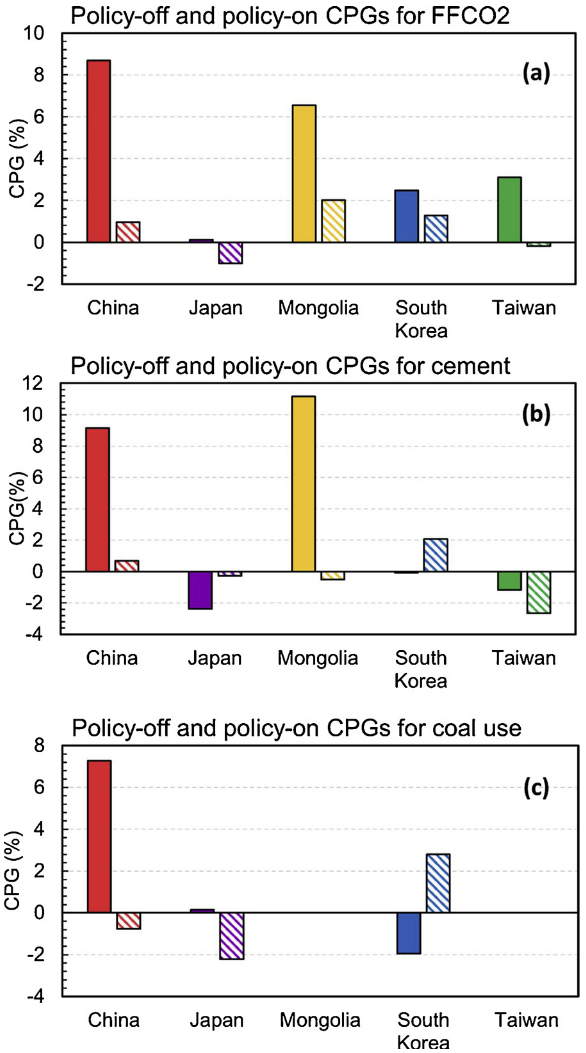

Fig. 3. CPGs for policy-on (solid) and policy-off (lined) periods shown by bars for China (red), Japan (Purple), South Korea (blue), Mongolia (yellow) and Taiwan (green) for FFCO$_2$ (top-left panel), cement production (top-right panel) and coal consumption (bottom panel).

Meanwhile, for policy-on scenario, the distribution of FFCO$_2$ is more even and the highly emitting cluster role will contribute ˜42–43% to total EA emissions.

The response to policy-on scenario varies from country to country. The highest sensitivity for policy enactment is evidenced in China (25%, 80% and 160% policy-off to policy-on FFCO$_2$ differences) for 2020, 2025 and 2030 respectively. For other countries, percentages are lower with Mongolia (14%, 42%, 76%), South Korea (4%, 10%, 17%) and Japan (3%, 10%, 16%) for the same years. From NDC standpoint, we estimate the progress of FFCO$_2$ reduction depending on the scenario that is reached by 2030. According to unconditional targets, Japan, South Korea and Mongolia have pledged to decrease FFCO$_2$ by 17%, 20% and 14% respectively by 2030 (hereafter we discuss the relative change of FFCO2 by 2030 comparing to 2010 level). For Japan, two projections are contrasted since policy-off scenario shows 1% increase and policy-on scenario shows 13% decrease in FFCO$_2$. Both policy-off and policy-on scenario show that in 2030, we would observe 53% and 31% increase in FFCO$_2$ in South Korea. For Mongolia, we also observe that both policy-off and policy-on scenario yield increase in FFCO$_2$ by 2030 (by 11% and 4% comparing with 2010). As seen, despite some projections (policy-on for Japan) show promising results, no cases can satisfy NDC pledges. China is not mentioned since it is harder to estimate their progress towards NDC. China established the emission intensity goal for decreasing CO$_2$ emission (i.e. economic-dependent) and assumption about economy dynamics is needed. Topmost, China pledges are sometimes viewed as unambitious since intensity-dependent goals are most likely automatically reached (CAT, 2018).

4.4. Sixteen scenarios of policy enactment in East Asia

We build all possible combinations of environmental policies (16 scenarios) based upon 2020, 2025 and 2030 projections of FFCO$_2$ distribution. In pure policy-on scenarios (i.e. all environmental policies are enacted), the lowest increment of FFCO$_2$ emissions are expected. Comparing to 2017, we would observe only 2.6%, 7.3% and 12.1% of FFCO$_2$ growth across EA by 2020, 2025 and 2030 respectively (see scenario 1 in Fig. 5). These numbers correspond to 18 752, 19 594 and 20 482 gC/m^2/d increments comparing to 2017 respectively. Reversely, for the scenarios without environmental policies being enacted (16th scenario in Fig. 5), the highest observable increase in FFCO$_2$ across EA is 26.1%, 86.7% and 178.4% by 2020, 2025 and 2030 respectively. The role of the policies strongly depends on the underlying national emitter. For instance, differences among scenarios that use 12th FYP of China (1–8 scenarios) are very small (˜ 0.1% for 2020, ˜1% for 2025 and 2030). Similarly, small difference is found across scenarios where 12th FYP is enacted. In contrary, the difference between FFCO$_2$ summarized emissions is very large (23%, 78% and 163% by 2020, 2025 and 2030 respectively) when only 12th FYP scenario and TMS + ISEE + 1st NAP (no 12th FYP) are compared. When the 12th FYP is excluded from the comparison, the most favorable scenarios are 9 (ISEE + NAP + MTS), 11 (ISEE + TMS) and 13 (NAP).

5. Study limitations

We note that CPG relies on the principle of steady growth in FFCO$_2$ emissions. If prognosis on summarized FFCO$_2$ emissions is drawn, the final estimates depend on the scale of spatial domain in CPG calculation. In most cases, it would not cause any additional uncertainties. However, for a large and strong national emitter, there can be additional uncertainties. We suspect that annual FFCO$_2$ growth of various provinces in China may considerably vary. To this end, we compare baseline projections (2020, 2025 and 2030) using two different CPGs (national and provincial scales). During 2011–2015, policy-on CPG of FFCO$_2$ in China is 1%. Same CPG value is observed in most provinces of China. Taiwan policy-on CPG is yet very different and equals to -0.2% (details shown in supplementary material). In national scales, policy-off CPG (2000–2010) is 8.7%. Median CPG for the same time interval across all provinces of China is 9.1% (from 7.1% in Heilongjiang to 12.9% in Tibet). CPG of Taiwan for policy-off period once again shows the highest contrast to mainland with CPG of FFCO$_2$ (3.6%). As a result, CPG-based prognosis may exhibit higher variability for policy-off than for policy-on scenario across China (and EA). In Fig. 6, we show the influence of different CPGs in China when projections of FFCO$_2$ across EA are made using national-scale CPG of China and provincial scale-on. Policy-on scenarios result in 2.3%, 2.1% and 2.0% bias across EA due to change in CPG. Policy-off scenarios are more sensitive and complicated in response and show 0.9%, -2.2%, -6.0% bias in EA due to changes in CPG. We note that positive bias represents higher emissions in national-scaled CPG and negative represents shift towards province-scaled CPG. These uncertainties are not critical, yet should be considered as CPG-based approach is further used for policy-making implications.

6. Discussion

In this study, we sought to understand how effective the current policy tools are for decreasing carbon emissions within single national economy in EA (in 2010–2017). We showed that the role of environmental policies of China (12th FYP), Japan (ISEE), South Korea (TMS) and Mongolia (1st NAP) is beneficial in terms of slowing down FFCO$_2$

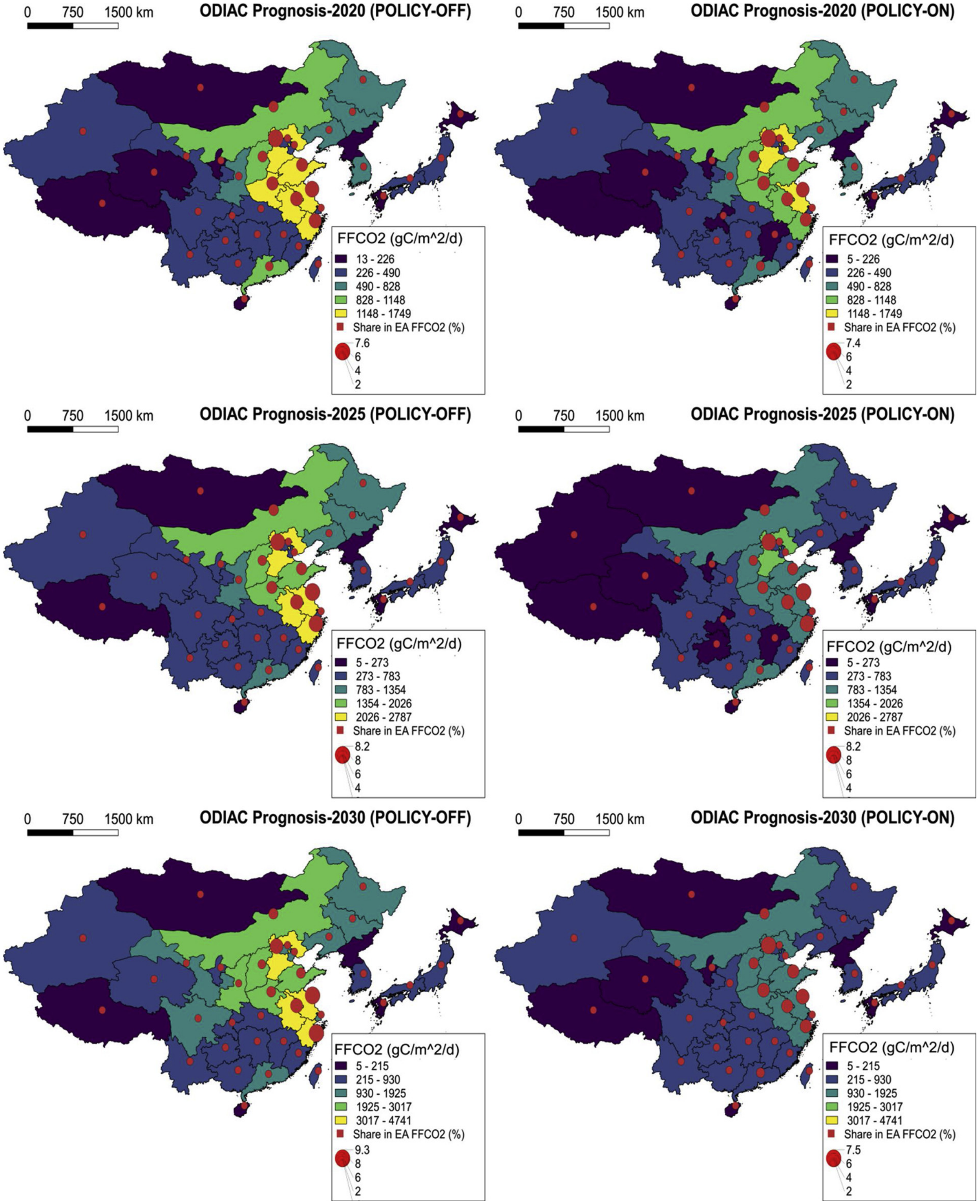

Fig. 4. ODIAC estimates of FFCO2 for 2020, 2025 and 2030 (from top to bottom) across EA for policy-off (left panel) and policy-on (right panel) using baseline projections. ODIAC FFCO$_2$ emissions (gC/m^2/d) are shown by blue-to-yellow color; red circles represent share of the region in total EA emissions (%).

growth. When these polices were enacted, the FFCO$_2$ growth has either slowed down (China, Mongolia, South Korea) or even turned to decline (Japan) comparing with prior periods. We present two baseline projections of FFCO$_2$ distribution across EA that relied on two different annual growth rates of FFCO$_2$ (CPG) calculated from the periods when environmental policies were enacted (policy-on) or not (policy-off). Policy-on projection is more promising since FFCO$_2$ in EA would be 24%, 80%, 166% lower than using policy-off projection (by 2020, 2025 and 2030 respectively). While all 16 policy-relevant scenarios are compared, the environmental policy importance is also supported. The pure policy-on scenario leads to the lowest increment of EA FFCO$_2$ emissions in near future. This scenario will result in 2.6%, 7.3% and 12.1% of FFCO$_2$ increment across EA by 2020, 2025 and 2030 respectively. The contrasted scenario without environmental policies yields in the highest FFCO$_2$ increase across EA (by 26.1%, 86.7% and 178.4% by 2020, 2025 and 2030 respectively).

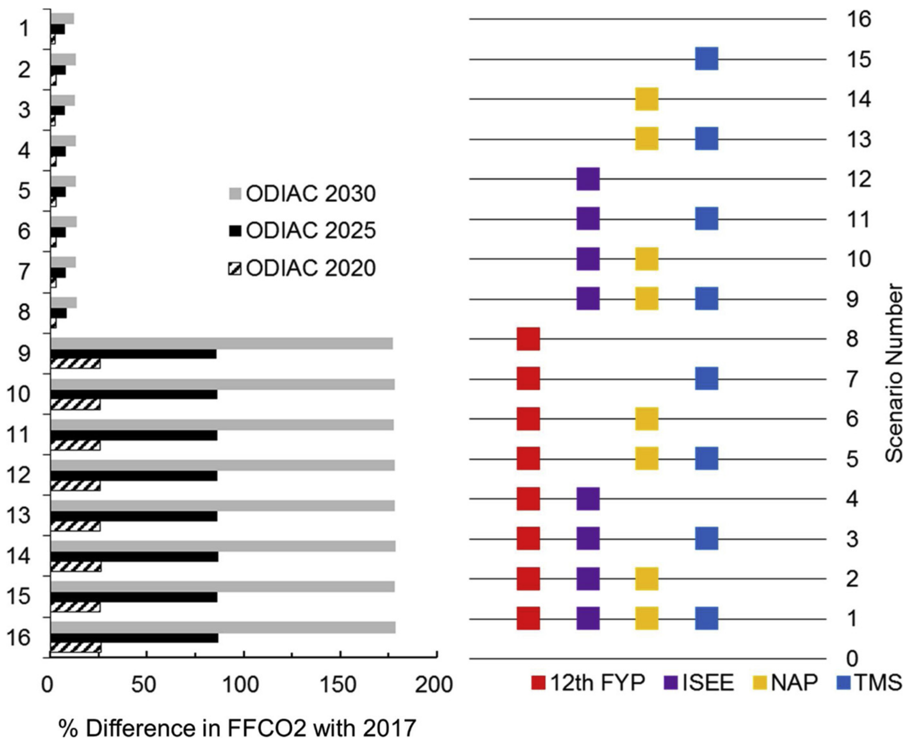

Fig. 5. Left panel: increase of $FFCO_2$ (%) across EA by 2020 (black and white), 2025 (black) and 2030 (gray) bars for 16 scenarios of $FFCO_2$ growth. Right panel: square represents "policy on" flag for each scenario (red - China, purple - Japan, yellow - Mongolia, blue - South Korea).

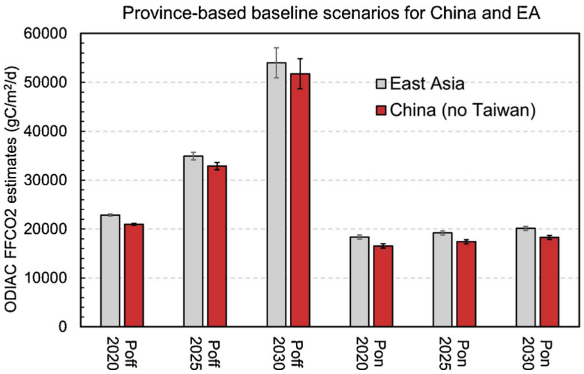

Fig. 6. Province-based baseline scenarios for the Mainland China and EA in 2020, 2025 and 2030. Error bars denote the difference between province-based and national-based estimates of CPG.

We determined which environmental policies had the highest impacts in terms of slowing down $FFCO_2$ emission growth across EA. The period of the strongest decrease in $FFCO_2$ emission growth of EA corresponds to 12th FYP of China (2011–2015). CPG of $FFCO_2$ has decreased from 8.7% (policy-off) to 1.0% (policy-on) in China. We found strong positive correlation ($r = 0.76$) between IAV of $FFCO_2$ of EA and IAV of coal production in China during 2011–2015. Results from 16 environmental policy scenarios supported the importance of 12th FYP. The difference between 8 scenarios that contain 12th FYP is only ~1% (2025, 2030). Meanwhile, the differences between the scenario that contains only 12th FYP and scenario that contains TMS, ISEE and 1 st NAP effect are 78% (2025) and 163% (2030). For other countries, we found that environmental policies are beneficial but less impactful for EA scales. Japan's median IAV of $FFCO_2$ is nearly zero during 2000–2017 period and future projections for Japan showed the lowest difference in national $FFCO_2$ emissions between policy-off and policy-on cases (3%, 10% and 16% by 2020, 2025 and 2030 respectively). For South Korea, IAV of $FFCO_2$ during TMS period shows the lowest variability and the differences in national $FFCO_2$ between policy-off and policy-on projections are relatively small (4%, 10% and 17% for 2020, 2025 and 2030 respectively). For Mongolia, the policy-off projection shows 14%, 42% and 76% increase in $FFCO_2$ by 2020, 2025 and 2030 respectively. We also found out that $FFCO_2$ variability in Taiwan shows decrease pattern (contrary to mainland China increase).

We assess the future consequences of environmental policies in EA in terms of $FFCO_2$ reduction required by NDC. Policy-off scenario results in stable increase of $FFCO_2$ for all countries with economically-independent pledges by 2030 (Japan, South Korea, Mongolia) and policy-on scenario shows decrease only for Japan (-13%). The decrease is insufficient comparing to NDC pledge of 17%. We observe that China is the most sensitive economy for environmental policy enactment. For policy-off scenario, $FFCO_2$ emissions are 25%, 80% and 160% higher in China than for policy-on scenario. The largest differences in $FFCO_2$ between policy-off and policy-on projections are registered in Jiangsu, Zhejiang, Hebei, Inner Mongolia, Henan, Shandong, Anhui and Shanxi of China ($>$ 200 $gC/m^2/d$ by 2020). Policy-off scenario shows that some of these provinces (Hebei, Jiangsu, Zhejiang, Anhui, Henan, Shandong) represent the cluster of the highest emissions in EA. If policy-off scenario is sustained, the share of this cluster to total EA emissions will be progressively increased (by 44%, 48% and 52% by 2020, 2025 and 2030 respective) contrary to policy-on scenario where the highly emitting cluster role would remain at 42–43% during these years.

7. Conclusions

Despite benefits of the environmental policies in terms of slowing down $FFCO_2$ emissions, they seem to be insufficient. Even the most favorable policy scenario leads to inevitable growth of $FFCO_2$ across EA since a relative increase of $FFCO_2$ over EA would be more than doubled by 2030 comparing to 2017. The increase will be evidenced in policy-on scenario of China, South Korea and Mongolia with a considerable decrease of emissions only in Japan. All the assumed policy-on $FFCO_2$ dynamics would likely lead to failing to achieve NDC targets by 2030.

Moreover, policy-on assumption implies that all environmental policies are simultaneously enacted in EA. Whilst, this was only the case of 2013–2015 and therefore carbon abatement activities could be occasionally beneficial during some years so the achieved progress is more fragile. We suggest that the lack of over-national supervision is driving fragmented success in carbon abatement by national economies in EA. Currently, a wide range of challenges in controlling carbon reduction goal achievement is faced by national governments in EA. Without the supranational framework, achievements in carbon emission reductions will be strongly hindered by the socioeconomic environment and the regional (or sectoral) emphasis of carbon reduction activities within a national economy.

China will have to face necessity to decrease $FFCO_2$ emissions in the economically developed regions (including the shown highly-emitting cluster). Stringent regionally-oriented emission constraints would most likely accelerate outsourcing of energy production to less-developed provinces of China (Lindner et al., 2013). Japan will have to prove that increased share of renewable energy (that government has credited for the emission decline) can return $FFCO_2$ to wane stage observed in 2015. We concern about that since the IEEE text states “most renewable energy sources are high cost and their supply is unstable in many cases”. South Korea being focused on highly-emitting firms has not yet achieved decrease in industrial carbon-rich activities such as coal use and cement production. For Mongolia, quality of the inventory data can suffer from unknown issues and detain their progress in achieving NDC goals. We observed that in one case interannual difference between cement production years exceeded 100% and standard deviation of IAV of cement production reached 47% (it is ˜5% for all other EA economies).

Ideally, there should be a solution for building up supranational framework that controls the carbon abatement and greenhouse gas reduction goals in EA, that will also help overcoming the aforementioned challenges faced by national economies. As a regulating body, this framework could (a) assign operative status of national environmental plans with carbon abatement goals based on numerical criteria, (b) help to align national environmental policies to the international pledges like Paris Agreement. As a supportive body, this framework could facilitate (a) linking a national-scale policy with key local measures for satisfying announced pledges (energy sector transformation, decarbonization of cities, introducing renewables), (b) implementing flexible region-specific carbon abatement goals developed specifically the geographic regions that face unique challenges (c) assisting governmental transitions from one party (or elite) to another within one country by re-evaluating new environmental policies that should not harm compliance of the international pledges (d) independently tracking dynamics of the carbon-driven output in economy such as energy consumption, transportation and industrial activities (e) evaluating quality of the submitted data from the country parties and require validation for compliance if needed.

Competing interests

The authors declare that they have no conflict of interest.

Acknowledgments

This work was supported by the Korea Meteorological Administration Research and Development Program “Research and Development for KMA Weather, and Earth system Services-Development and Assessment of AR6 Climate Change Scenarios” under Grant (KMA2018-00321). We acknowledge the team of the Center for Global Environmental Research (National Institute for Environmental Studies of Japan) for their efforts in providing ODIAC free-access CO_2 emission estimates (http://db.cger.nies.go.jp/dataset/ODIAC/DL_odiac2018.html).We appreciate assistance of Takeshi Kuramochi, Sergey Victorov and Shewaya Breckell during the manuscript preparation.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.envsci.2019.03.011.

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