ENVIRONMENTAL STUDIES

Clean air for some: Unintended spillover effects of regional air pollution policies

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China has enacted a number of ambitious pollution control policies to mitigate air pollution in urban areas. Unintended side effects of these policies to other environmental policy arenas and regions have largely been ignored. To bridge this gap, we use a multiregional input-output model in combination with an atmospheric chemical transport model to simulate clean air policy scenarios and evaluate their environmental impacts on primary $PM_{2.5}$ and secondary precursor emissions, as well as CO_2 emissions and water consumption, in the target region and spillover effects to other regions. Our results show that the reduction in primary $PM_{2.5}$ and secondary precursor emissions in the target regions comes at the cost of increasing emissions especially in neighboring provinces. Similarly, co-benefits of lower CO_2 emissions and reduced water consumption in the target region are achieved at the expense of higher impacts elsewhere, through outsourcing production to less developed regions in China.

INTRODUCTION

The World Health Organization (WHO) reported that outdoor air pollution was responsible for the premature deaths of some 3.7 million people in 2012. One in eight premature global deaths is related to air pollution exposure (*1*–*4*), demonstrating that air pollution is now the single largest environmental health risk worldwide (*5*, *6*). $PM_{2.5}$ is responsible for almost half of air pollution–related deaths, most of which are in Asia (*5*, *7*). Moreover, premature mortality caused by $PM_{2.5}$ pollution is frequently due to production of exports (*8*). For example, more than 108,600 premature deaths related to $PM_{2.5}$ in China are caused by production for exports to Western Europe and the United States (*9*). China's coal-based energy-intensive development path has led to a steep increase in $PM_{2.5}$ emissions and its precursors (*7*, *10*), resulting in 1.6 million deaths from heart and lung diseases or stroke, approximately accounting for one in six premature deaths in China (*11*). Specifically for Beijing, Tianjin, and Hebei [also referred to as Jing-Jin-Ji (JJJ)], the national capital region, the annual average concentration of $PM_{2.5}$ is 93 $\mu g/m^3$ (*12*), which is almost 10 times higher than the WHO standard (10 $\mu g/m^3$) (*13*).

To comply with the national strategic objective of a 10% reduction in $PM_{2.5}$ concentration by 2017 relative to 2012 levels, JJJ established an ambitious target of a 25% $PM_{2.5}$ concentration reduction and released a clean air policy to restrict coal consumption and eliminate pollution-intensive industries (Fig. 1A) (*14*). A reduction in $PM_{2.5}$ emissions requires the mitigation of primary $PM_{2.5}$ emissions and secondary aerosols, which are oxidized from precursor emissions (*10*) such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), ammonia (NH_3), and nonmethane volatile organic compounds (NMVOCs) (*15*, *16*). Examples of these mitigation efforts include the shutdown of all coal-fired power plants and their replacement by four gas thermoelectric power plants in Beijing and an increase in the share of imported electricity from 30% in 2012 to 70% in 2017, mainly from Inner Mongolia and Shanxi through the extra-high-voltage transmission connection (*14*, *17*).

However, at the same time, there might be negative spillover effects to other regions, as closing down and migrating electricity, steel, and cement production plants out of the target region might lead to outsourcing and pollution leakage to less developed regions with less efficient technology and lower environmental standards (*18*, *19*), potentially leading to detrimental overall effects nationally. In addition to potentially ignoring spatial spillover effects, environmental policy focusing on a single pollutant might cause unintended nexus effects related to other policy arenas (*18*). Research has shown that there are links between air quality and climate change within the food-water-energy nexus (*20*, *21*) and thus a potential for co-benefits between pollution control policies and climate change mitigation (*22*–*25*). For example, outsourcing heavy- and highly polluting industries from JJJ for local air pollution reduction goals would also help to achieve regional CO_2 emission targets. At the same time, this would increase imports from other, often less developed, regions with less efficient technology, lower environmental standards, and more carbon-intensive fuel mix, with an overall negative effect on achieving national CO_2 reduction targets (*18*). Similarly, when looking at another key environmental issue, which is the overuse of water resources, we find a similar situation. JJJ's per capita water availability is only one-eighth of the national average, with 12.3% of shallow freshwater overexploitation (*26*, *27*). Currently, 38% of physical water (2014) (*28*) and 45% of virtual scarce water (2012) consumed by JJJ are imported from other regions via the South-North Water Transfer Project and the trade of water-intensive products between different regions, some of which have surplus water, whereas others suffer from even more severe water shortages (*29*).

As heavy-polluting industries consume 10% of the total water supply in Beijing (*26*), 20% in Tianjin (*27*), and 12% in Hebei (*28*), the implementation of clean air policies may alleviate local water shortages but unintentionally intensify water stress elsewhere (*30*). That is,

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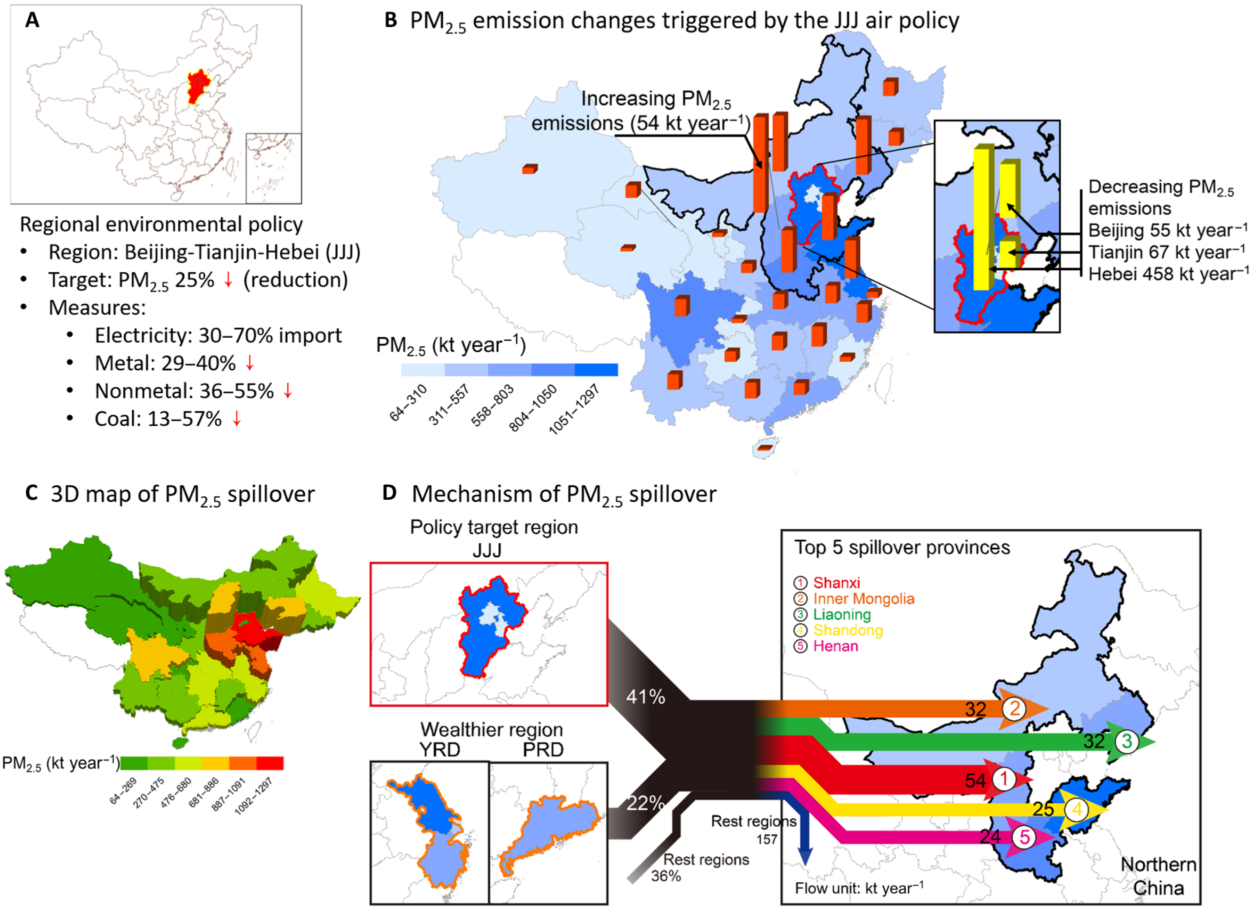

Fig. 1. Primary $PM_{2.5}$ emission changes triggered by the JJJ clean air policy. (**A**) JJJ clean air policy. Red part shows the JJJ region. (**B**) Primary $PM_{2.5}$ emission changes triggered by the JJJ clean air policy, with regions shaded according to primary $PM_{2.5}$ total emissions. Yellow bars show the reduction in primary $PM_{2.5}$ emissions in JJJ, and red bars show the increase in primary $PM_{2.5}$ emissions in the rest of China. (**C**) Three-dimensional map of primary $PM_{2.5}$ spillover from JJJ to other regions. (**D**) Mechanism of primary $PM_{2.5}$ spillover from the policy target region (JJJ) and wealthier regions (YRD and PRD) to northern China. The colored arrows show the direction and amount of primary $PM_{2.5}$ spillover to the provinces of Shanxi, Inner Mongolia, Liaoning, Shandong, and Henan.

ambitious but single-minded regional environmental policies may lead to additional outsourcing and pollution leakage as well as unintended spillover effects into other environmental policy arenas.

$PM_{2.5}$ primary and precursor emissions in a single region not only influence aerosol pollution locally but also are amplified by atmospheric pollution transport, potentially from remote areas (*31*, *32*). As the increase in secondary inorganic pollutants has been observed as pollution haze in several cities in eastern China (*10*), the geographical scope of the haze could be extended by wind-transporting pollutants. Therefore, haze episodes in JJJ could be affected by polluted air masses originating from different source regions such as northeastern China, Shandong, or coastal China (*33*). It has been shown that about half of Beijing's air pollution originates from emission sources outside of the municipality (*34*). Therefore, these outsourced emissions to neighboring regions could potentially migrate back to the target region via atmospheric transport and so contribute to a backfire effect.

Integrated environmental evaluation approaches, combining multiregional input-output (MRIO) analysis and atmospheric transport modeling, can provide holistic policy suggestions as they enable tackling multiple environmental elements simultaneously and mitigating unanticipated influences upon other regions or sectors (*35*). MRIO provides a widely used approach for tracking embodied emissions or virtual resource use in regional, national, or global supply chains (*36*, *37*) and enables the investigation of the effects of outsourcing on natural resources and emissions (*18*). In this study, we use environmental MRIO to evaluate the regional clean air policy in China's capital region (JJJ) in terms of regional reduction in air pollution as well as nexus effects on CO_2 emissions and consumption of scarce water. We developed scenarios in accordance with the JJJ clean air policy within the MRIO framework through reducing domestic production of target sectors while increasing the imports from other parts of China to satisfy final demand of the JJJ region. We evaluate these policy scenarios in terms of primary $PM_{2.5}$ emissions and precursor emissions of secondary $PM_{2.5}$ pollution (SO_2, NO_x, NH_3, and NMVOCs) for JJJ as well as other regions in China. This study combines flows of primary $PM_{2.5}$ and secondary precursor emissions using MRIO combined with an atmospheric chemical transport model, i.e., the nested-grid Goddard Earth Observing System - Chemistry (GEOS-Chem) model, which simulates pollution concentrations at high resolution and the atmospheric transport of spillover emissions in regions surrounding the JJJ area. In addition, the unintended effects on other intertwined environmental problems, i.e., carbon emissions and water stress, are also taken into consideration. A schematic diagram of this study is given in fig. S1. We expect that these regional polices will have regional benefits at the expense of neighboring regions and, potentially, nationally.

RESULTS

Primary $PM_{2.5}$ emission reduction in JJJ

Under the clean air policy scenario in the JJJ region, domestic primary $PM_{2.5}$ emissions of Beijing, Tianjin, and Hebei are estimated to decline, respectively, by 41% (55 kt), 35% (67 kt), and 33% (458 kt) compared with the business-as-usual (BAU; 2012) scenario. For the JJJ region, primary $PM_{2.5}$ emissions from the electricity sector would decline by 13%, mining and refining of metals by 33%, production of nonmetal products by 47%, and residential activities by 36% compared with BAU.

Spillover effects of primary $PM_{2.5}$ emissions

As hypothesized earlier, these regional clean air policies developed in isolation might lead to detrimental effects in other provinces and at the aggregate national level due to shifting pollution to regions with less advanced technologies. Although primary $PM_{2.5}$ emissions in JJJ would decrease by 34% (580 kt), primary $PM_{2.5}$ emissions in the rest of China would increase by 2.5% (323 kt) compared with BAU, in contrast to the national primary $PM_{2.5}$ reduction target of 10% in 2017 (*14*). In the rest of China, primary $PM_{2.5}$ emissions in the electricity sector would increase by 2.1% (70 kt), emissions in the metal sector would increase by 4.8% (129 kt), and the nonmetal sector would emit an extra 1.9% (74 kt).

Figure 1B maps the current primary $PM_{2.5}$ emissions in China (bar charts show the changes of primary $PM_{2.5}$ emissions in each province). Figure 1C shows emission spillover resulting from the JJJ clean air policy. Most of the emission increase would happen in JJJ's neighboring provinces, which are already shrouded in haze and ranked in the top 10 primary $PM_{2.5}$-polluted regions in China. For example, Shanxi's primary $PM_{2.5}$ emissions would increase by 8% (or 54 kt), Inner Mongolia by 8% (32 kt), Liaoning by 5% (32 kt), Shandong by 2% (25 kt), and Henan by 2% (24 kt). These provinces would contribute almost three quarters of additional primary $PM_{2.5}$ emissions in China.

The spillover works in two ways (Fig. 1D). The JJJ region outsources pollution for the production of its own final demand (and that way contributing 40% of the primary $PM_{2.5}$ emission increase in northern China), and then, the JJJ region also outsources some parts of its role in national supply chains, i.e., export production for other regions [e.g., for final demand in other rich regions such as the Yangtze River Delta (YRD) (Shanghai, Jiangsu, and Zhejiang) and Pearl River Delta (PRD) (Guangdong)], and so contributing another 22% of the primary $PM_{2.5}$ emission increase in northern China.

Spillover effects of $PM_{2.5}$ precursor emissions

The results of the $PM_{2.5}$ precursor emissions show that the annual NH_3, NO_x, SO_2, and NMVOC emissions in JJJ would decline by 0.2% (2 kt), 16% (362 kt), 20% (529 kt), and 4.3% (82 kt), respectively. However, the emissions of NH_3, NO_x, SO_2, and NMVOCs in the rest of China would increase by 0.45% (57 kt), 2.0% (379 kt), 2.2% (565 kt), and 1.3% (255 kt), respectively. This shows that the JJJ clean air policy would lead to higher emissions in other regions.

Figure 2 maps the current NH_3, NO_x, SO_2, and NMVOC emissions in each province. It shows that substantial spillover effects were caused by the JJJ clean air policy.

Atmospheric transport of outsourced emissions

Outsourced emissions to northern China could potentially end up back in the JJJ region due to atmospheric transport and could thus contribute to a rebound or even a net increase in $PM_{2.5}$ concentration within the target region. On the basis of the emissions estimated above, we simulate the pollutant concentration via the atmospheric model in January, as it is the most polluted month in China (*10*). Figure 3C shows the influence of the JJJ clean air policy on ambient $PM_{2.5}$ concentration without the impact of outsourced emissions, indicating that the $PM_{2.5}$ concentration in JJJ would decrease by up to 10 μg/m^3 compared with BAU. However, in southern Hebei, which neighbors Shanxi, Henan, and Shandong, the $PM_{2.5}$ concentration would increase by approximately 1 to 2 μg/m^3 (Fig. 3B2). This is due to the atmospheric transport of outsourced emissions especially to northern China, with $PM_{2.5}$ concentration increasing in Shanxi, Henan, and Inner Mongolia by 2 to 5 μg/m^3. This atmospheric transport of outsourced emissions from neighboring regions would contribute to the $PM_{2.5}$ concentration in JJJ with an increase of 0.1 to 2 μg/m^3, especially in southern JJJ (for more information on air pollution transport, see the Supplementary Materials, part 9) (Fig. 3B).

Unintended nexus effects on CO_2 emissions and water resources

JJJ's air pollution control, with a main focus on reduction in coal combustion, is also designed to help achieve the ambitious goal of cutting back carbon intensity (*38*, *39*). In addition to reduction in $PM_{2.5}$ emissions, JJJ attains co-benefits through a decline of CO_2 emissions by 18% (168 Mt), mainly in electricity (12%, 41 Mt), metal (33%, 100 Mt), and nonmetal (40%, 26 Mt) production sectors. However, these gains would be more than compensated nationally through importing these products from areas with higher carbon intensities. Not surprisingly, these additional CO_2 emissions would mainly be outsourced to neighboring provinces such as Shanxi, which would show a 10% (43 Mt) increase in CO_2 emissions, Inner Mongolia a 6% increase (36 Mt), Liaoning a 5% increase (21 Mt), Henan a 2% increase (11 Mt), and Shandong a 1% increase (12 Mt) (Fig. 4). However, these neighboring provinces already face higher carbon intensities with an average value of 260 g/¥, which is more than 1.6 times the national level. Thus, JJJ's attempts to reduce $PM_{2.5}$ emissions would inadvertently make it more difficult for neighboring regions to achieve their own CO_2 emission reduction targets.

Target sectors, such as coal-fired power plants and energy-intensive industries, not only are major sources of air pollution but also require lots of water during production processes. Here, we focus on virtual scarce water, i.e., water consumed during the entire supply chain weighted by its impact on water scarcity or water stress, to analyze the nexus effect on water resources. Water stress is defined as the ratio of total annual freshwater withdrawals to hydrological availability, ranging from 0 (no stress) to 1 (severe stress) (*29*, *40*).

The JJJ clean air policy might save scarce water resources by 5.4% (128 Mm^3), i.e., 4.4% (24 Mm^3) in Beijing, 4.3% (13 Mm^3) in Tianjin, and 6.0% (91 Mm^3) in Hebei. Although the JJJ clean air policy might ameliorate local groundwater depletion and coincide with the Three Red Lines goals of water resource conservation (*41*), it would also lead to an increase in water scarcity elsewhere. Because

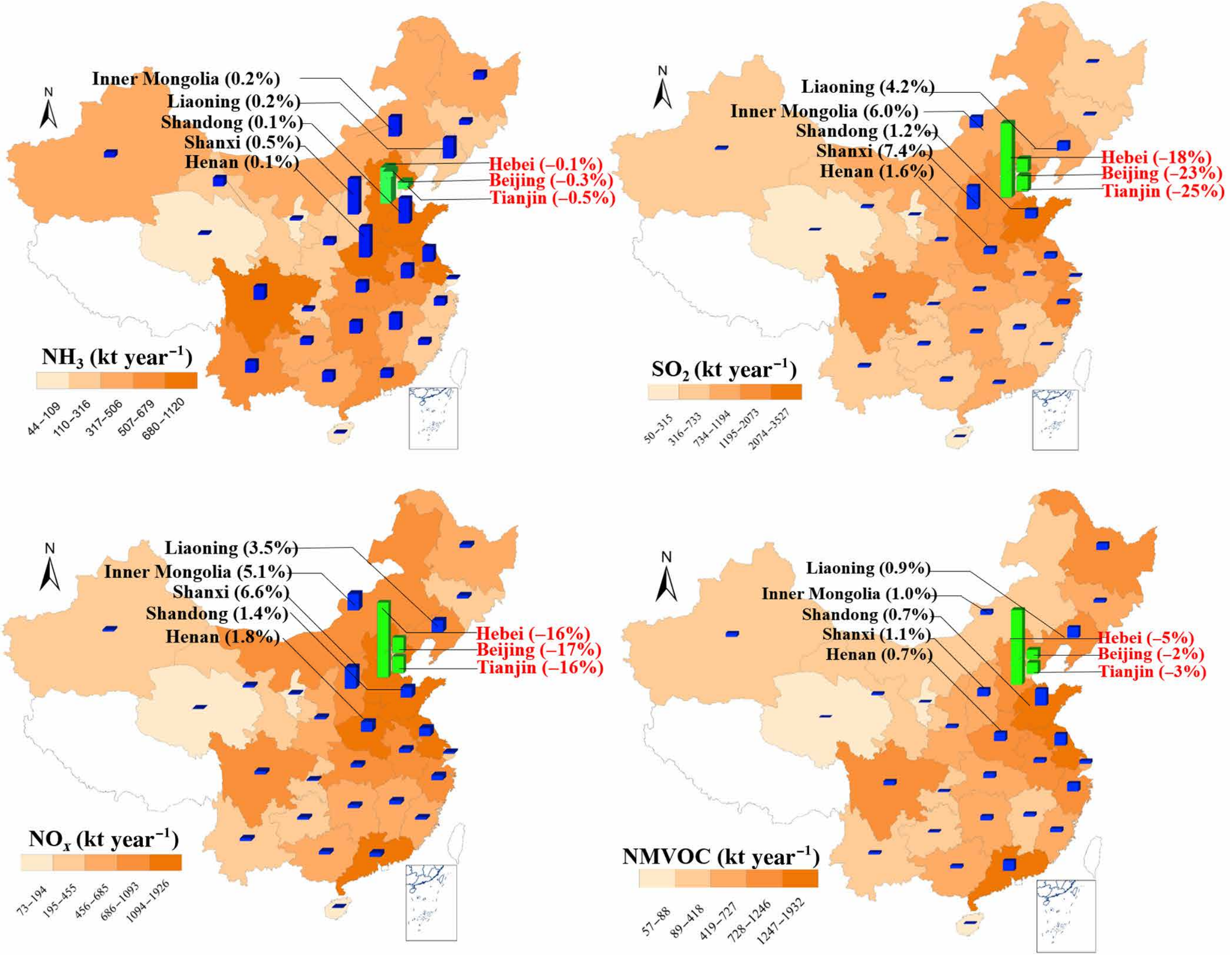

Fig. 2. NH_3, NO_x, SO_2, and NMVOC emission changes triggered by the JJJ clean air policy. Green bars show the decrease in NH_3, NO_x, SO_2, and NMVOC emissions in JJJ, and blue bars show the increase in $PM_{2.5}$ emissions in other regions, with regions shaded according to total NH_3, NO_x, SO_2, and NMVOC emissions.

of outsourcing of production to other regions, national scarce water consumption would increase by 1.3% (239 Mm^3). Figure 5 shows that the JJJ clean air policy might increase water pressure elsewhere and potentially threaten the water conservation status in these provinces. For example, Shanxi, Inner Mongolia, Jiangsu, Liaoning, and Henan would export more scarce water resources embodied in trade, with an increase of 1 to 8% (29 to 95 Mm^3). Most of these provinces are in serious water scarce conditions, with water stress indexes higher than 0.9 (*29*). Accordingly, the JJJ clean air policy would be implemented with the caveat to potentially increase water stress in other regions unintentionally.

Spillover effects at the sectoral level

The spillover index (SPI) is the ratio of the additional pollution or resource consumption in other regions triggered by the regional policy over the pollution or resource decrease in the policy target region (without the pollution or resource reduction directly from residential activities). Figure 6 illustrates that the increase in primary $PM_{2.5}$ emissions in the other regions is 1.6 times higher than the reduction in JJJ (i.e., SPI = 1.6). This increase is mainly driven by the additional production of metal smelting (SPI = 3.0) and nonmetal products (SPI = 2.0), which are likely to be outsourced to less developed regions in China with lower environmental standards and less efficient technologies. The secondary $PM_{2.5}$ precursor emissions show similar effects. The NH_3, NO_x, SO_2, and NMVOC emissions would increase in other regions, which are, respectively, 3.5, 1.9, 2.1, and 2.5 times larger than the emission reduction in the JJJ region.

A similar situation can be found when looking at CO_2 emissions. Figure 6 shows that the CO_2 emission reduction in JJJ would create 3.6 times more CO_2 emissions in the other regions. This additional CO_2 mainly comes from metal smelting (SPI = 2.8) and nonmetal products (SPI = 3.6). Thus, closing down and outsourcing heavy- and highly polluting industries for JJJ's air pollution reduction reduce local carbon emissions at the expense of emissions elsewhere, resulting in an overall negative effect on achieving carbon reduction targets. We find the same situation with water as well. Figure 6 shows that the increase in scarce water consumption in other regions is 2.9 times higher than the initial reduction in JJJ, which is mainly caused by the outsourcing of metal smelting (SPI = 3.0) and metal mining (SPI = 3.2). The increase in primary $PM_{2.5}$ emissions, NH_3 emissions, NMVOC emissions, and scarce water consumption for electricity production in the other regions is similar to the decrease in JJJ, meaning that increasing the share of electricity imports to JJJ would improve environmental quality at the expense of

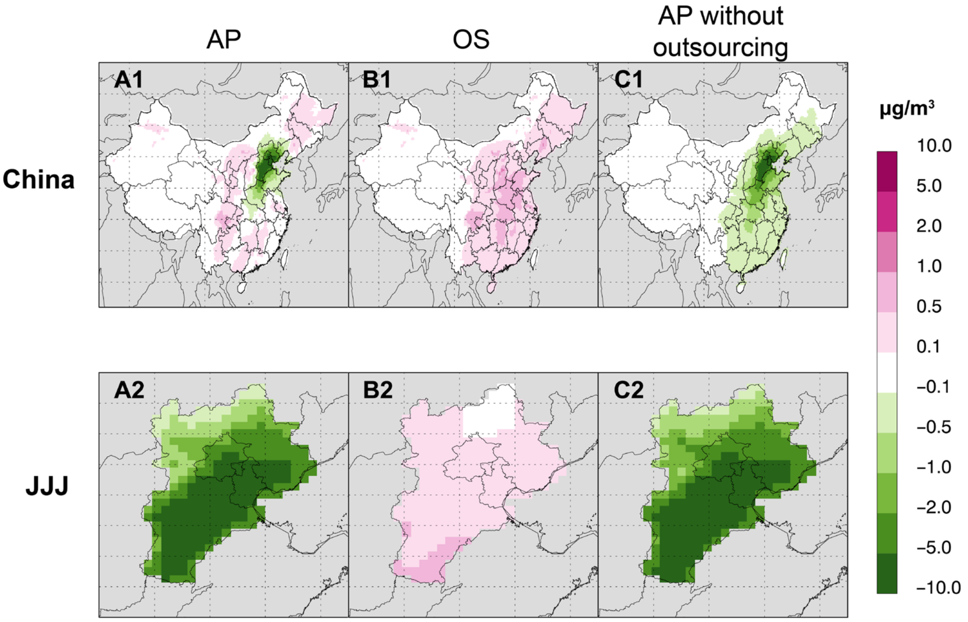

Fig. 3. Simulated change of surface air pollution in China. (**A1**) JJJ clean air policy impact, (**B1**) effect of outsourced emissions, and (**C1**) without outsourced emissions. (**A2**, **B2**, and **C2**) Maps zooming into the JJJ region. All figures include effects from changes in production and atmospheric transport of pollutants. Results are shown for monthly mean concentration of surface $PM_{2.5}$ in January. The color scale is nonlinear to better present the wide range of impacts over different regions. The ambient $PM_{2.5}$ concentration across China is simulated by the GEOS-Chem model using emissions under BAU, JJJ clean air policy scenario (AP), and outsourcing effects (OS) scenario (table S5). (A1) AP shows the overall changes of $PM_{2.5}$ concentration due to the impacts of the JJJ clean air policy. (B1) OS shows the increase in $PM_{2.5}$ concentration due to outsourcing, i.e., increase in production and pollution in the rest of China and associated atmospheric transport of pollution. (C1) AP without outsourcing illustrates the reduction in $PM_{2.5}$ concentration due to the JJJ clean air policy without taking into consideration outsourcing of emissions to other regions in China.

other regions but would not increase total national impacts. On the other hand, the notable reduction in metal and nonmetal production in JJJ not only would affect other regions but also would lead to net negative environmental effects at the national level, such as extra air pollution, CO_2 emissions, and water stress.

DISCUSSION

Our research demonstrates the potential unintended spillover effects of a regional environmental policy to neighboring regions and beyond while also highlighting the side effects on other environmental factors, such as CO_2 emissions, water consumption, and water stress.

The JJJ clean air policy targets coal-fired power plants and heavy industries with potential environmental co-benefits with respect to reduction in $PM_{2.5}$ emissions, CO_2 emissions, and scarce water conservation within the target region. The scenario for air pollution mitigation developed in this study shows that the $PM_{2.5}$ reduction is about 34%, which is close to the actual measures (39% reduction) (Supplementary Materials, part 12). In addition to helping JJJ meet the ambitious goal of $PM_{2.5}$ concentration reduction by 25%, the clean air policy helps reduce carbon emissions (20.5%) (*39*) and ameliorate groundwater depletion, which coincides with the Three Red Lines goals of water resource conservation (*41*).

However, without considering the unintended side effects of isolated environmental policies, these might backfire and lead to an increase in environmental problems in other regions as well as an overall increase in pollution nationwide. Currently, JJJ is already outsourcing 53% of consumption-based primary $PM_{2.5}$ emissions to surrounding and less affluent provinces in northern China. The additional spillover primary $PM_{2.5}$ emissions from JJJ to other regions is 3.4 times larger than the reduction in domestic emissions from JJJ, and the overall primary $PM_{2.5}$ emissions would increase by 1.6% in China.

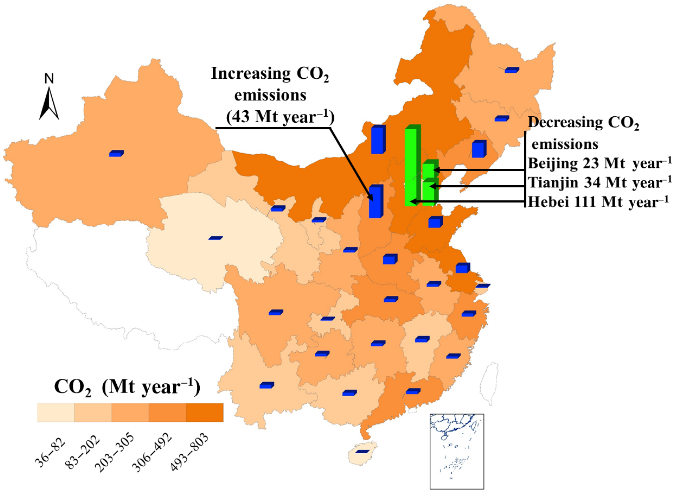

Fig. 4. CO_2 emission changes triggered by the JJJ clean air policy. Green bars show the decrease in CO_2 emissions in JJJ, and blue bars show the increase in $PM_{2.5}$ emissions in other regions, with regions shaded according to total CO_2 emissions.

Our research shows that the spillover effect caused by the regional policy mainly consists of two types. One is the direct shift of pollution-intensive enterprises from the target region to regions with lower environmental standards and inferior technologies. Similarly, if a number of affluent regions simultaneously implement stringent environmental policies, then less developed areas will suffer even more severe pollution spillover. For example, China's clean air policy enacted more stringent $PM_{2.5}$ reduction targets in affluent regions—i.e., JJJ (25%), YRD (20%), and PRD (15%)—than the reduction targets in less affluent cities (10%). It is economically rational to issue relatively lenient environmental requirements in less developed regions; however, precisely because of these regionally different standards of environmental policy, more serious pollution spillover would occur, that is, regions with higher standards would import even more pollution-intensive products from regions where air quality policy is less stringent.

Another important aspect of the pollution problem is related to the topological characteristics that amplify the problem and the pervasiveness of pollution haze in the North China Plain (*33*, *42*). Because of its valley topography, JJJ receives $PM_{2.5}$ pollution through the prevailing winds from urban areas and satellite towns such as Liaoning, Shandong, Henan, and Shanxi (*43*), but it also exports pollution to other regions not only virtually but also through exporting polluted air masses, further questioning the wisdom of regional air pollution control policies. Our results also indicate that outsourced emissions would be transported back to the JJJ area through atmospheric transmission and would partially or fully offset the reduction in $PM_{2.5}$ concentration in JJJ. Therefore, control measures ensuring air quality in a specific region or city have to be designed on a transregional scale.

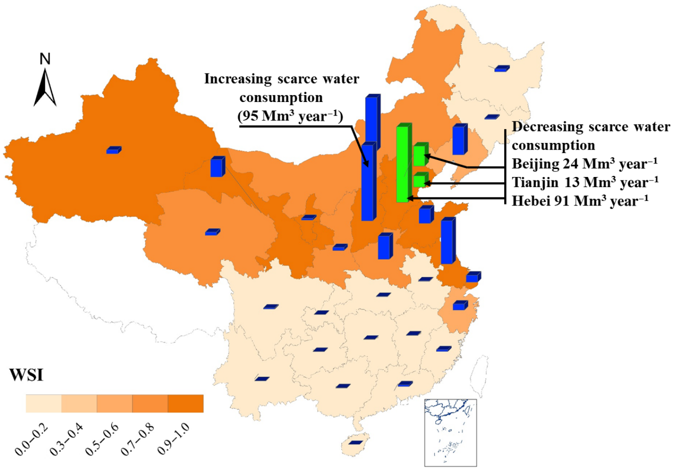

Fig. 5. Scarce water consumption changes triggered by the JJJ clean air policy. Green bars show the decrease in scarce water consumption in JJJ, and blue bars show the increase in scarce water consumption in other regions, with regions shaded according to the water stress index (WSI).

In addition to spatial spillover effects, the JJJ clean air policy would result in nexus effects in terms of climate change and water scarcity. As environmental factors are not only tightly intertwined in a complex system of interacting physical, chemical, and biological processes but also through interlinked production activities through interregional trade networks, policies targeting a single environmental factor would potentially create unintended side effects in other environmental policy arenas.

The separate regulation of environment factors limits the effectiveness of managing resources and pollution. The fragmented and overlapping governance structure of environmental protection in China hampers tackling the teleconnected and cross-sectional nature of environmental problems. For example, China's Ministry of Environmental Protection has established separate environmental departments for water, air, and soil (*44*), while carbon tax and emissions trading systems are supervised by the National Development and Reform Commission, and water resources are overseen by the Ministry of Environmental Protection and the Ministry of Water Resources (*45*). Our research illustrates that this regulation of separate environmental factors might lead to unexpected outcomes due to outsourcing pollution to other regions and unintended nexus effects to other environmental issues. Therefore, a comprehensive multiregional joint governance approach that takes into account the unequal distribution between affluent and less developed regions with a vision beyond a regional and single-problem focus for comprehensive environmental protection is needed.

Because different authorities at various levels (local, regional, and national) are concerned with and manage environmental issues separately and only within their respective jurisdictions, the spillover effects on other environmental factors or other regions are frequently ignored (*46*). There are several key considerations for decision-makers to propose environmental policies, such as (i) linkages between environmental factors, (ii) influence scale, (iii) benefits and trade-offs, and (iv) regional-to-global teleconnections. Most of the industrial processes involving combustion will not only emit air pollutants and CO_2 but also consume water and other natural resources, so a larger range of relevant pollutants and natural resources should be evaluated to determine how the policy will jointly affect different environmental arenas (*21*). Because of the location of the pollution source, the

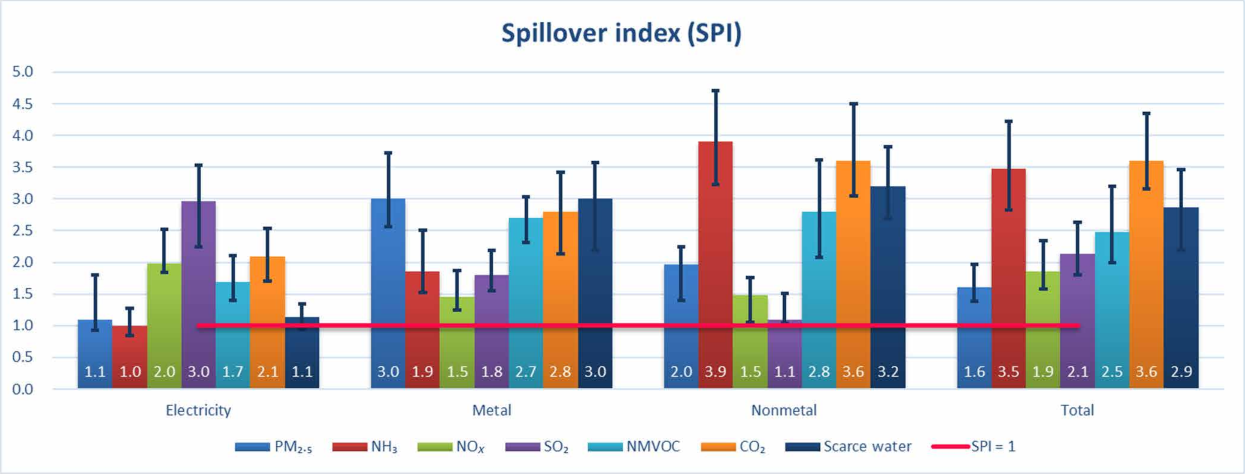

Fig. 6. Spillover effects of the JJJ air policy at the sectoral level. SPI of major sectors and total production and associated uncertainty levels.

environmental conditions (e.g., atmospheric conditions and dispersion of pollution patterns), and the properties of natural resources, environmental effects do not follow specific administratively defined boundaries. Joint consideration of regional and larger-scale environmental goals should be given. For example, a regional air pollution reduction strategy should not act against larger national and global agreements or negatively affect other regions (*47*). There is a potential dilemma between different environmental arenas (*20*). For example, second-generation biofuels are considered as carbon neutral or even carbon negative, while their production processes consume large amounts of water, and combustion of biofuels can lead to an increase in NO_x emissions. Furthermore, cross-regional trade networks can transfer environmental impacts to other regions, and these linkages lead to spillover effects of regional environmental policies (*48*). Moreover, environmental policies will create social and economic impacts along global supply chains (*49*, *50*). Therefore, multicriteria and multiregional considerations as presented in our study provide a comprehensive framework to coordinate actions on air pollution control, climate change mitigation, and conservation of natural resources, as well as provide information on local efforts and their impacts and conformity with national strategies.

MATERIALS AND METHODS

MRIO analysis

We used the MRIO approach, which allowed us to model the environmental impacts of various policy scenarios considering the entire supply chain and pollution and resource consumption at each production stage (*51*). The MRIO approach has been widely used to assess embodied pollution or natural resources in regional or global trade, such as primary $PM_{2.5}$ emissions (*52*, *53*), $PM_{2.5}$ precursor emissions (*15*, *16*), CO_2 emissions (*18*, *54*), and water consumption (*29*, *40*), among a long list of other environmental factors (*55*). Using the MRIO can help identify and quantify environmental outsourcing from richer regions to less developed regions via tracking the emission/resource flows through regional, national, and global supply chains. This research uses China's MRIO 2012 table to establish a scenario of JJJ air pollution control action plan, with the MRIO 2012 setting as the basis for the BAU scenario.

JJJ clean air policy scenario

The clean air policy for JJJ aimed to reduce $PM_{2.5}$ concentration by 25% in 2017, compared with the level in 2012, via measures such as increased electricity imports and phasing out of heavy industry based on outdated technologies. For electricity, all coal-fired power plants in Beijing are planned to be shut down and replaced by gas thermoelectric power plants. The shares of imported electricity in Beijing and Tianjin were predicted to be over 70 and 35% in 2017, which are mainly imported from Inner Mongolia and Shanxi through the extra-high-voltage transmission connection (*14*, *17*). Coal combustion for both residential and industrial activities would decline in Beijing (57%, 13 Mt), Tianjin (20%, 10 Mt), and Hebei (13%, 40 Mt). The steel and cement production capacity was planned to be reduced by 29 to 40% and 36 to 55%, respectively, via phasing out heavy industries with old technologies in JJJ (Supplementary Materials, part 2). The comparison of the actual emission reduction measures and the modeled measures was implemented in the Supplementary Materials, part 12.

In the MRIO analysis, the planned structural changes under the clean air policy are linked to the relevant sectors in each region via an explicit representation of changes in the production or consumption of the target sectors. For example, if domestic electricity production in Beijing was planned to decline, then this would lead to an increase in imports, at least in the short run. To model this change, the column (inputs for production) of Beijing's electricity production would be scaled down, and electricity imports from other regions to Beijing would be increased to account for the shortfall. For other regions, to meet the increase in electricity exports, the column of their electricity would be scaled up to keep the balance of input and output of that sector. Then, the RAS technique, also known as a "biproportional" matrix balancing technique, which is widely used in updating input-output information, was applied to keep the balance of the MRIO (*51*) (Supplementary Materials, part 3). The technical coefficient matrix, i.e., **A** matrix, of MRIO will be changed on the basis of the implementation of each policy action, and then the new interprovincial fluxes from region *r* to region *s* can be calculated, i.e., PM^{rs} (clean air policy). The difference between PM^{rs} (clean air policy) and PM^{s} (BAU) can be used to reflect the reduction in primary $PM_{2.5}$ in the target region, as well as the amount of outsourced emissions in other regions. The same evaluation can be applied to CO_2 and scarce water.

Atmospheric chemical transport modeling

We designed three atmospheric simulations to analyze the impacts of the JJJ clean air policy on $PM_{2.5}$ concentration across China (table S5). BAU is the baseline scenario using production-based emissions for the prepolicy situation (or status quo in year 2012). The AP scenario represents the intended policy outcome, estimates pollution for JJJ based on environmental policy measures (i.e., BAU minus reduction in target sectors), and shows the overall changes of $PM_{2.5}$ concentration in the rest of China due to the impacts of the JJJ clean air policy. In the outsourcing scenario, the JJJ clean air policy would lead to increases in production and pollution in the rest of China. The comparison between the outsourcing scenario and BAU illustrates the atmospheric transport of additional outsourced emissions in neighboring regions due to the JJJ clean air policy (for more information, see table S5). We applied the GEOS-Chem atmospheric chemical transport model (version 11-01) to evaluate the atmospheric transport of outsourced emissions (attributable to the JJJ clean air policy) from the neighboring regions to the JJJ region in January using the emission data calculated in various atmospheric simulation scenarios. More descriptions of the GEOS-Chem simulation process are provided in the Supplementary Materials, part 6.

Data sources

The 2012 China MRIO table was constructed on the basis of China's original provincial input-output tables 2012 (*56*, *57*). In addition, the interregional trade flow matrix was estimated using a hybrid technique based on a maximum entropy and gravity model (*58*, *59*). The MRIO table contains 30 provinces (except Tibet, Hong Kong, Macau, and Taiwan due to lack of data) with 42 economic sectors for each province, which has been used in previous studies (*60*, *61*) (see the Supplementary Materials, part 4). Primary $PM_{2.5}$, SO_2, NO_x, NH_3, and NMVOC emission data were obtained from the Greenhouse Gas–Air Pollution Interactions and Synergies (GAINS) model developed by the International Institute for Applied Systems Analysis (IIASA) (*62*), the spatial distribution and information on the monthly variation of emissions were derived from the Multi-resolution Emission Inventory for China (MEIC) (*63*), carbon emission data were obtained from the China Emission Accounts and Datasets (CEADs) (*64*), virtual scarce water data were calculated on research by Feng *et al.* (*29*), and the water scarcity index was calculated based on Pfister *et al.* (*65*) (see the Supplementary Materials, part 5, for a detailed calculation of emission and scarce water consumption factors).

The descriptions of uncertainties and limitations are provided in the Supplementary Materials, part 10, including emission inventory estimation, air pollution control scenario assumptions and SPI, and modeling of atmospheric transport. The emissions estimated in this study are generally consistent with the MEIC v.1.2 emission inventory (*63*), which supports several international research projects such as MICS and HTAP and has been widely used for air pollution analysis in China and Asia (*9*, *31*, *52*). Our results on interprovincial emission flows are generally consistent with the studies by Zhao *et al.* (*16*). Details of these analyses are presented in the Supplementary Materials, part 11.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/5/4/eaav4707/DC1

Table S1. JJJ clean air policy measures.

Table S2. Concordance matrix from GAINS sectors to MRIO sectors.

Table S3. Concordance matrix from GAINS sectors to MEIC sectors.

Table S4. Concordance matrix from MRIO sectors to MEIC sectors.

Table S5. Definitions of various atmospheric simulations used in atmospheric transport modeling.

Table S6. Comparison of the actual and modeled JJJ emission reduction measures.

Fig. S1. Schematic methodology for analyzing the spatial spillover and nexus effects of the JJJ clean air policy.

Fig. S2. $PM_{2.5}$ spillover effects of the JJJ clean air policy at the regional level.

Fig. S3. Simulated surface air pollution in China.

Fig. S4. Comparison of production-based emission estimates of this work (2010) and MEIC v.1.2 (2010) by sector and by region.

Fig. S5. Comparisons between the simulated and observed monthly mean $PM_{2.5}$ concentration.

Fig. S6. Comparison of regional pollutant emissions from production- and consumption-based perspective (kt year^{-1}).

Fig. S7. Comparison of JJJ's emissions generated by interprovincial exports with the research of Zhao *et al.*

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