SUPPLEMENTARY INFORMATION
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Air quality co-benefits of carbon pricing in China

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Supplementary Information:
Air Quality Co-benefits of Climate Policy in China

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S1 Methods

Sensitivity of emissions to emissions factors changes. We conducted three additional simulations to examine the sensitivity of emissions in the No Policy scenario to emissions factors changes. First, we keep emissions factors fixed at their 2015 level. A comparison between this simulation and the No Policy scenario is shown in Figure S1. Without emissions factors changes, No Policy emissions show large increases: BC is 95% higher, and OC is 140% higher in 2030, reflecting the absence of existing policies aimed at reducing biomass burning in agricultural areas. Other pollutant species also show substantial increases by 2030: 59% for SO_2, 21% for NO_x, and 29% for NH_3. A second and third scenario double and triple, respectively, the emissions decay factors. We find that SO_2 emissions fall by 36% and 58%, NO_x emissions fall by 14% and 25%, NH_3 emissions by 20% and 35%, BC by 26% and 42%, and OC by 13% and 22% in the No Policy scenario by 2030, in the two respective cases.

S2 Regional Outcomes

We report the full set of regional difference between the No Policy and 4% Policy in consumption, energy use, CO_2 emission, and $PM_{2.5}$ concentration in 2030 in Figures S3 and S4. Percentage changes of total $PM_{2.5}$ and anthropogenic $PM_{2.5}$ with respect to percentage changes of CO_2 emission are shown in Figure S5. Table S5 lists avoided mortalities in each province under the 4% Policy, and the net benefit by taking the difference between the policy cost and monetized health benefit. The provinces are sorted based on GDP per capita in 2010, as a proxy for average household wealth.

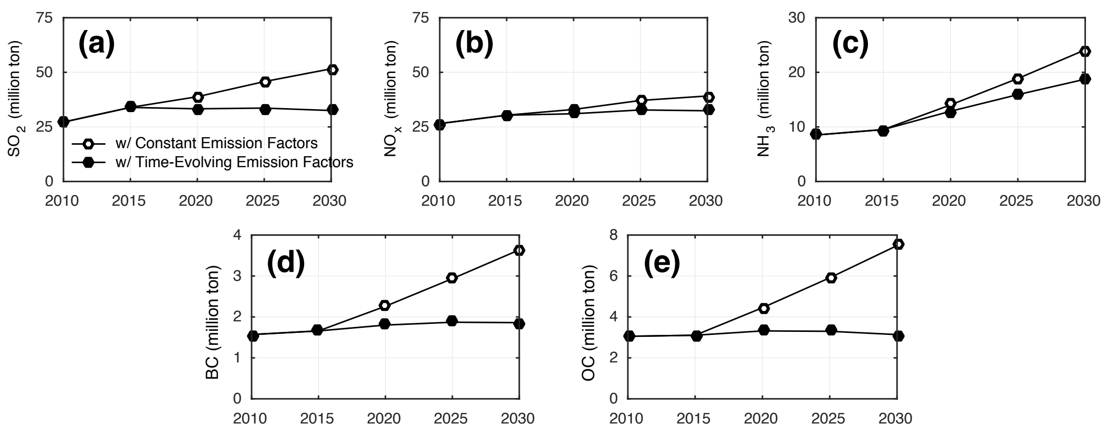

Figure S1: Comparison of emissions trajectories with time-evolving emissions factors and constant emissions factors.

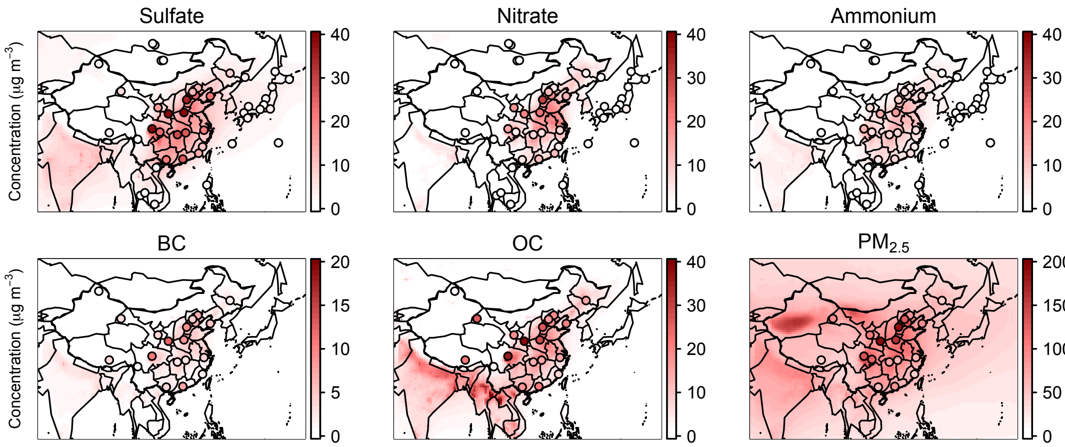

Figure S2: Simulated annual mean surface concentrations in East Asia for the year 2010 (sulfate, nitrate, ammonium, BC, OC, and total $PM_{2.5}$). Circles indicate locations and concentrations of measurements used for model comparison.

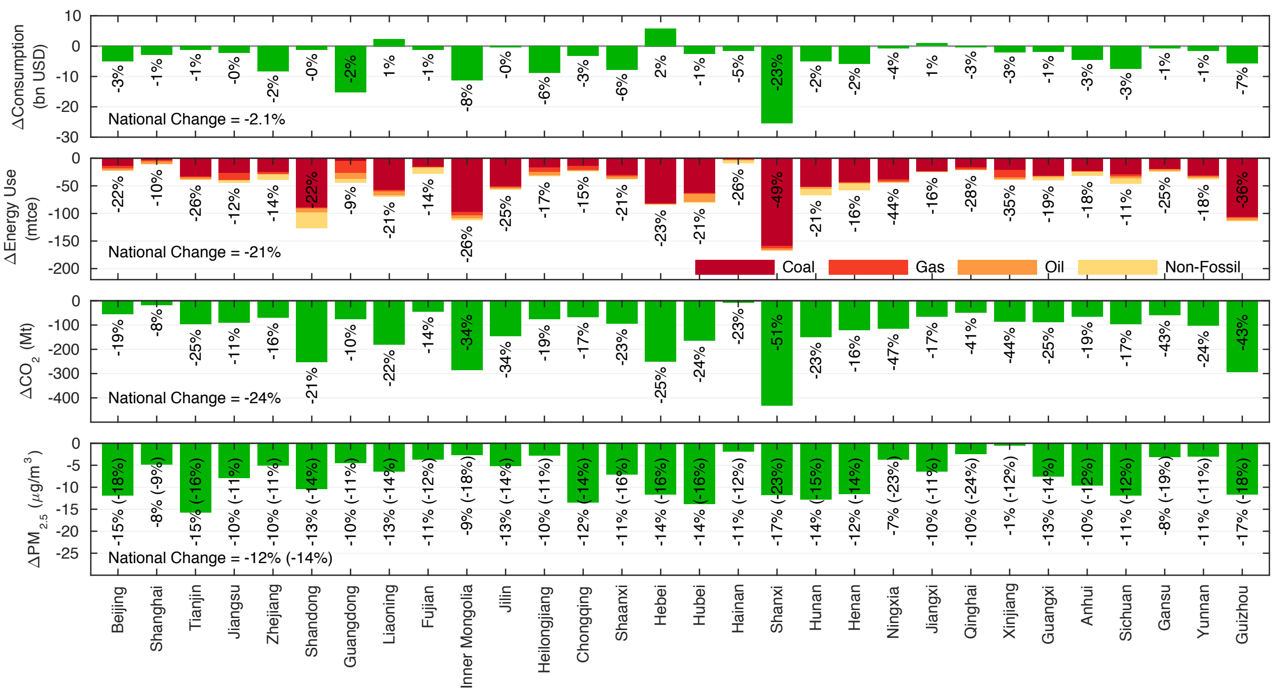

Figure S3: Changes in multiple outcomes due to the 4 % Policy, compared to the No Policy scenario in 2030. From top to bottom: consumption, energy use, CO_2 emission, and population-weighted total $PM_{2.5}$ concentration. Numbers beside each bar represent percentage changes, and numbers inside the parentheses in the bottom panel are percentage changes in terms of anthropogenic $PM_{2.5}$.

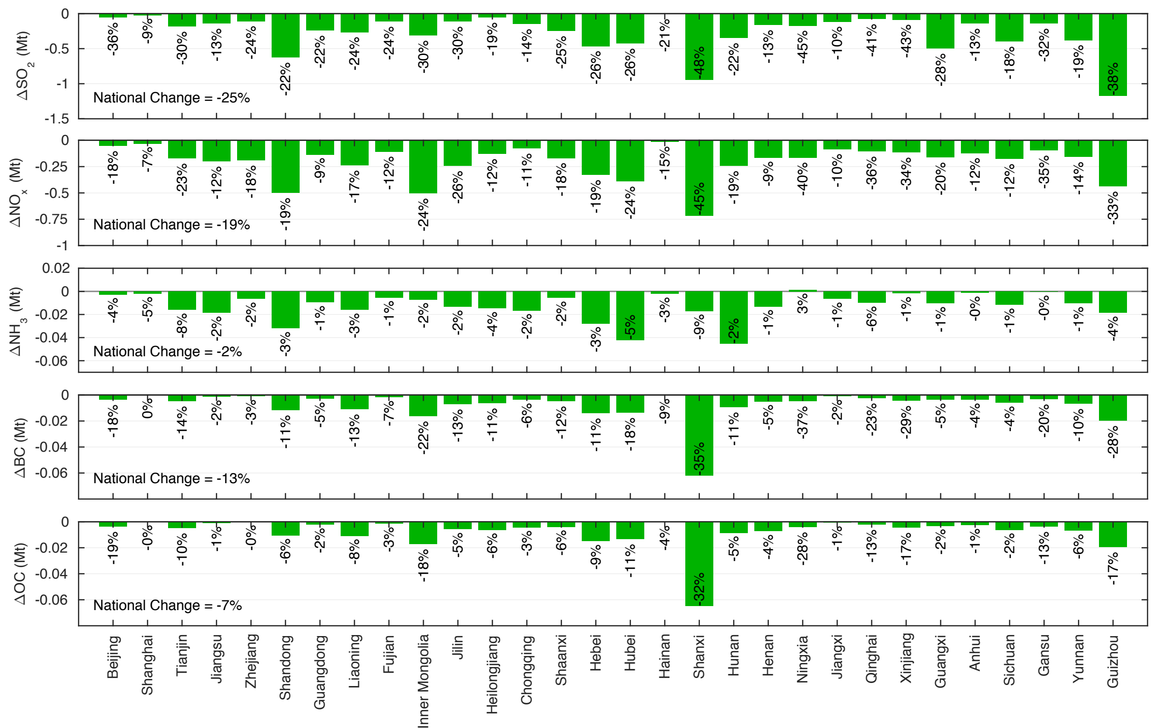

Figure S4: Changes in precursor emissions due to the 4 % Policy, compared to the No Policy scenario in 2030. Numbers beside each bar represent percentage changes.

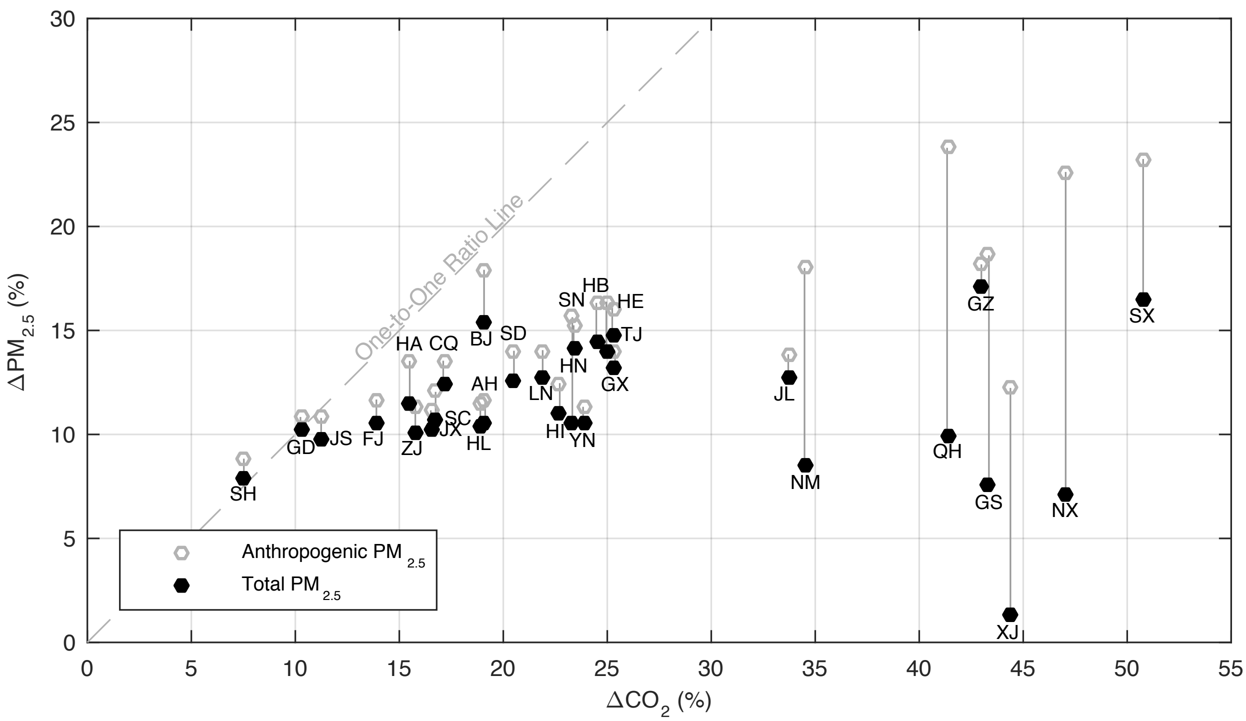

Figure S5: Percentage changes of $PM_{2.5}$ vs. CO_2 due to the 4% Policy, compared to the No Policy scenario in 2030.

Table S1: Regional and sectoral aggregation in C-REM

Regional	Sectoral (description in parenthesis)
Chinese mainland provinces	**Energy**
Anhui (AH)	COL (Coal mining and processing)
Beijing (BJ)	CRU (Crude petroleum products)
Chongqing (CQ)	GAS (Natural gas products)
Fujian (FJ)	OIL (Petroleum refining, coking, and nuclear fuels)
Guangdong (GD)	**Non-energy**
Gansu (GS)	AGR (Agricultural, forestry, and livestock)
Guangxi (GX)	CON (Construction)
Guizhou (GZ)	EIS (Energy intensive industries)
Henan (HA)	ELE (Electricity and heat)
Hubei (HB)	MAN (Other manufacturing industries)
Hebei (HE)	OMN (Metal/non-metal minerals mining)
Hainan (HI)	SER (Service)
Heilongjiang (HL)	TRN (Transport and post)
Hunan (HN)	WTR (Water supply)
Jilin (JL)	
Jiangsu (JS)	
Jiangxi (JX)	
Liaoning (LN)	
Inner Mongolia (NM)	
Ningxia (NX)	
Qinghai (QH)	
Sichuan (SC)	
Shandong (SD)	
Shanghai (SH)	
Shaanxi (SN)	
Shanxi (SX)	
Tianjin (TJ)	
Xinjiang (XJ)	
Yunnan (YN)	
Zhejiang (ZJ)	
Other regions	
United States	
Europe	
Other developed countries or regions*	
Rest of the world	

*It includes Australia, Canada, Japan, New Zealand, Singapore, South Korea, and Taiwan.

Table S2: Sectoral mapping between REAS and C-REM.

Sectors in REAS*	**Sectors in C-REM**
AGR_FORE, AGR_FORE_FISH, AGRICULT, ENTERIC_FERMENTATI, FERT_PROD, FERTILIZER, FISHING, MANURE_MANAGEMENT, RICE_CULTIVATION	AGR
CRUDE_OIL	CRU
GAS_PROD, NATURAL_GAS, OTHER_GAS	GAS
DIESEL_OIL, KEROSENE, HEAVY_FUEL_OIL, MOTOR_GASOLINE, OTHER_HF, OTHER_LF	OIL
LIME, MINING, NON_MET_MINE	OMN
ADIPIC_ACID, ALUMINUM_ALUMINA, BRICKS, CEMENT, CERAMICS, COKE_OVENS, CRUDE_STEEL, IRON_AND_STEEL, NITRIC_ACID, NON_FERROUS_METAL, IRON_STEEL_OTHERS, NON_SPECIFIED, PIG_IRON, STEEL, SULPHRIC_ACID	EIS
POWER_PLANTS	ELE
AMMONIA, AMMONIUM_NITRATE, CHEM_PETRCHEM, CHEMICAL_IND, CHEMICAL_MATERIAL, CHEMICAL_PRODUCT, COPPER, DEGREASING, EXTRAC_PROC, FOOD, GLASS, INK_PROD, LEATHER, LEAD, MANUFACTURING, OTH_TRANSFORMATION, OTHER_PROD, OTHER_USAGE, OTHERS, PAINT_PROD, PAPER, PLASTIC, PRINTING, RUBBER, SMALL_INCIN TEXTILE, UREA, WASTE, WASTE_INCIN, ZINC	MAN
WASTE_WATER	WTR
CAR_EVAP, DOM_NAVI, RAILWAY_ETC, ROAD_BUSES, ROAD_H_TRUCKS, ROAD_L_TRUCKS, VEHICLE	TRN
COMM_PUB, COMMERCIAL, DRY_CLEANING	SER
DOM, PET_DOG, RESIDENT, ROAD_CARS, ROAD_MC, ROAD_OTHERS	c

* Full names and detailed description of sectors in REAS can be found in: http://www.nies.go.jp/REAS/.

Table S3: Trend parameter for emissions factors to decay exponentially over time

Pollutant Species	**Trend Parameter**
SO_2	-0.03
NO_x	-0.01
NH_3	-0.015
BC	-0.03
OC	-0.03
Biomass	-0.07

Table S4: Correlation coefficient and bias between annual mean concentrations of model and observations

Species	**Correlation (r)**	**Bias (model-observation)**
Sulfate	0.92	-27%
Nitrate	0.79	-31%
Ammonium	0.91	15%
BC	0.74	-44%
OC	0.63	-42%
$PM_{2.5}$	0.68	-13%

Table S5: Avoided mortality, policy cost, and health benefit by province in 2030 under the 4% Policy. References refer to alternative sources for underlying exposure-response relationships.

Province	**Avoided Mortality**			**Consump. Loss***	**Health Co-Benefit***	**Net Benefit***
	ref [1]	ref [2]	ref [3]			
Beijing	1113	331	2443	5.0	9.4	4.4
Shanghai	558	23	175	2.9	4.5	1.6
Tianjin	691	299	2185	1.3	4.9	3.6
Jiangsu	2196	1053	7833	2.3	13.0	10.8
Zhejiang	3282	699	5240	8.3	20.7	12.5
Shandong	4692	2280	16860	1.3	23.0	21.8
Guangdong	10383	1196	8971	15.2	53.7	38.5
Liaoning	3878	1437	10745	-2.4	17.1	19.5
Fujian	4785	546	4106	1.3	22.3	21.1
Inner Mongolia	3181	1342	10100	11.2	18.5	7.3
Jilin	3616	1209	9070	0.3	15.2	14.8
Heilongjiang	5766	1129	8505	8.9	26.8	18.0
Chongqing	1503	1246	9171	3.1	8.5	5.3
Shaanxi	1451	1802	13449	7.8	11.2	3.4
Hebei	4637	2822	20853	-5.8	13.6	19.4
Hubei	3551	3005	22088	2.6	15.6	12.9
Hainan	1522	84	635	1.6	6.2	4.5
Shanxi	2906	2262	16701	25.4	33.1	7.7
Hunan	3635	3578	26335	5.0	17.1	12.1
Henan	3913	2525	18631	5.8	20.3	14.6
Ningxia	248	231	1736	0.7	1.6	0.9
Jiangxi	1873	1396	10421	-1.0	6.3	7.3
Qinghai	781	194	1466	0.5	3.0	2.6
Xinjiang	1465	158	1196	2.0	6.4	4.3
Guangxi	3224	2402	17893	1.9	12.8	10.9
Anhui	2041	1647	12213	4.5	11.1	6.5
Sichuan	5300	3096	22844	7.5	24.5	17.0
Gansu	1888	852	6404	0.8	6.5	5.7
Yunnan	6938	1303	9793	1.5	22.7	21.2
Guizhou	3442	2111	15560	5.6	14.8	9.2
National	94459	42258	313622	125.0	464.5	339.6

*Consumption loss, health co-benefit, and net benefit are reported in billion USD. Health co-benefit and net benefit are calculated using the exposure response function in Burnett et al. (2014) [1].

References

[1] Burnett R. T. et al. An Integrated Risk Function for Estimating the Global Burden of Disease Attributable to Ambient Fine Particulate Matter Exposure. *Environ. Health Perspect.* **122**, 397–403 (2014).

[2] Cao J. et al. Association Between Long-Term Exposure to Outdoor Air Pollution and Mortality in China: a Cohort Study. *J. Hazard. Mater.* **186**, 1594–1600 (2011).

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