

Tracing the sources of air pollutant emissions embodied in exports in the Yangtze River Delta, China: a four-level perspective

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1 **Tracing the sources of air pollutant emissions embodied in exports in the Yangtze**
2 **River Delta, China: A four-level perspective**

3
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20
21 **Abstract:** Investigating the net effects of foreign trade on the local environment
22 requires a multiscale perspective. Increasingly, scholars have been investing effort to
23 establish a global–national–local system of linkages or a local–nonlocal division of
24 linkages. However, analysis at the megaregion level has somehow been overlooked,
25 although megaregions play a substantial role in the context of accelerating regional
26 integration and increasing regional pollution. This study incorporated megaregions into
27 the existing multiscale input-output model and constructed a four-level analytical
28 framework to analyze the emissions embodied in exports (EEE) in the Yangtze River
29 Delta (YRD) region. Since this region pioneered the economic transition in China, this
30 study further applies structural decomposition analysis (SDA) to investigate the
31 structural changes in EEE. The empirical results show that EEE in the YRD region was
32 mainly affected by local and cross-border linkages, which account for 85.1% and 9.8%
33 of the total EEE in the region. The increase in local EEE linkages needs to be reduced
34 by local technological innovation in sectors such as light industry and energy. To

35 prevent the YRD from becoming a pollution haven for developed countries, the cross-
36 border EEE linkage must be reduced by adjusting the production and consumption
37 structure of light industry. Cross-regional EEE linkage can be reduced through
38 technology upgrades in the construction sector. The trend of a decrease in intraregional
39 linkage and an increase in cross-regional linkage indicates that YRD exports tend to be
40 outward rather than inward oriented. The four-level framework for examining EEE
41 offers new detailed insights into the mitigation of regional air pollution.

42

43 **Keywords:** Pollution embodied in exports; Multilevel perspective; Input-output model;
44 Structural decomposition; Yangtze River Delta

45

46 **Highlights:**

- 47 • A four-linkage framework based on MRIO was developed to trace the sources of
- 48 EEE.
- 49 • Local and cross-border linkages accounted for most of the total EEE in the YRD.
- 50 • The pollution haven trend from developed countries to China's coastal regions
- 51 became weaker.
- 52 • EEE in the YRD was mainly influenced by the energy and metal manufacturing
- 53 sectors.
- 54 • Local emission reduction relied on technology upgrade and structure optimization.

55

List of Acronyms

EEE	Emissions Embodied in Exports
YRD	Yangtze River Delta
SDA	Structural Decomposition Analysis
MSIO	Multiscale Input-Output Model
MRIO	Multiregional Input-Output Model
TE	Technology Effect
PSE	Production Structure Effect
CSE	Consumption Structure Effect
SE	Scale Effect

56

57 **1 Introduction**

58 Since 2010, China has become the largest exporter worldwide, after serving as the
59 world's factory for decades (Guan et al., 2009). Increasing overseas demand
60 simultaneously placed an additional burden on China's eco-environmental conditions
61 (Lin et al., 2014; Zhang et al., 2017). The term "emissions embodied in trade" in the
62 literature captures such additional burdens (Baiocchi et al., 2012; Peters and Hertwich,
63 2006). Based on transnational input-output linkages and the context-dependent
64 coefficients of emissions (Zhong et al., 2018), the trade-induced relocation of emissions
65 across economies has been measured (Meng et al., 2018), especially between developed
66 and developing economies (Lin et al., 2014). Studies of the emissions embodied in trade
67 have accumulated evidence for the ongoing debate over the well-known pollution haven
68 hypothesis (Cai et al., 2018; Yang et al., 2019a). These studies are also helpful for
69 identifying the shared producer and consumer responsibilities for trade-induced
70 environmental effects (Pan et al., 2008).

71 Nevertheless, there is increasing awareness of the multiscale nature of the
72 international division of labor (Antràs and Hillberry, 2012; Mao and He, 2019). That is,
73 the network of international trade not only connects trading economies (Daumal, 2013)
74 but also reshapes connections between interior regions (Zhong et al., 2018). When
75 exposed to trade openness, interior regions essentially integrate with global markets in
76 addition to domestic ones (Shao et al., 2017). To examine the environmental effects of
77 trade at the local level, recent studies have established a multiscale input-output model
78 (MSIO) (Chen et al., 2013; Li et al., 2016). Empirical findings from studies of urban
79 carbon accounting (Shao et al., 2016), energy consumption (Li et al., 2019), and virtual
80 water (Han et al., 2015) also support the rationale behind, as well as the necessity of,
81 incorporating multiscale connections.

82 The multiscale perspective is especially relevant for economies with vast
83 territories such as China, which is undergoing processes of globalization, regional
84 integration, and economic transition (Mao and He, 2017; Wu et al., 2017). The
85 multiscale connections of interior regions can intertwine, working together to determine
86 the net environmental impacts of trade openness (Hubacek et al., 2014). For instance,
87 the export-oriented development model benefits the coastal regions of China, but they
88 must simultaneously carry the additional environmental burden induced by increasing
89 overseas demand from developed economies with emissions embodied in exports (EEE)

90 (Liu and Wang, 2015; Su and Thomson, 2016). However, continuous development in
91 these regions also draws resources to concentrate there and reshapes the spatial division
92 of labor. As such, these regions are also capable of transferring emissions to other
93 developing economies or regions and thus also of serving as the origin of embodied
94 emissions (Davis and Caldeira, 2010; Guo et al., 2012). Regarding this point, previous
95 studies at different scales provide mixed empirical findings. Some studies reveal that
96 inland regions in China have relatively lax environmental regulations, which lead to the
97 transfer of the environmental burden from the coast to the inland (Yang et al., 2012;
98 Zhu et al., 2014). In contrast, others find that the unique advantages of coastal regions
99 due to locational fundamentals supports the continuous development of both traditional
100 and emerging sectors (Wang and Zhao, 2015). Considering the above, examining the
101 net effects of multiscale linkages is essential to investigate the effects of trade openness
102 on the regional environment.

103 The question that follows is how many different scales should be considered to
104 capture the net effects of embodied emissions? Early studies at the national level
105 consider a nation to be a homogeneous entity and allow internal inequality to be easily
106 ignored (Liu and Wang, 2017; Stern, 2004). Recent studies shift their focus from the
107 national level (Feng et al., 2013) to the level of subnational regions, such as provinces
108 (Meng et al., 2013) or cities (Chen et al., 2013). Multiscale linkages tend to cover the
109 division of both local and nonlocal linkages or the hierarchical systems of global–
110 national–local linkages (Li et al., 2018a). However, considering the accelerating pace
111 of regional integration, neither the local–nonlocal division nor the global–national–
112 local system directly incorporates the level of megaregions. For instance, in some
113 developed regions in China, such as Beijing–Tianjin–Hebei, the internal region has
114 formed a division of labor, cooperation and interdependency. Due to Beijing’s and
115 Tianjin’s high imports from Hebei, industrial production in Beijing and Tianjin has led
116 to the transfer of more pollutant emissions to Hebei (Zhao, et al., 2016a). In this way,
117 despite the reduced emissions from Beijing and Tianjin, pollution emissions still remain
118 in the region, and the pollution problem for the whole region has not been resolved,
119 with the consequence of a “local reduction but regional rise” in emissions. Thus, it is
120 necessary to incorporate the regional level into the conventional MSIO, which tends to
121 be at the city level (Lin et al., 2017). Correspondingly, this study incorporates the
122 megaregion level and proposes a four-scale framework, covering the local, regional,
123 national, and global levels.

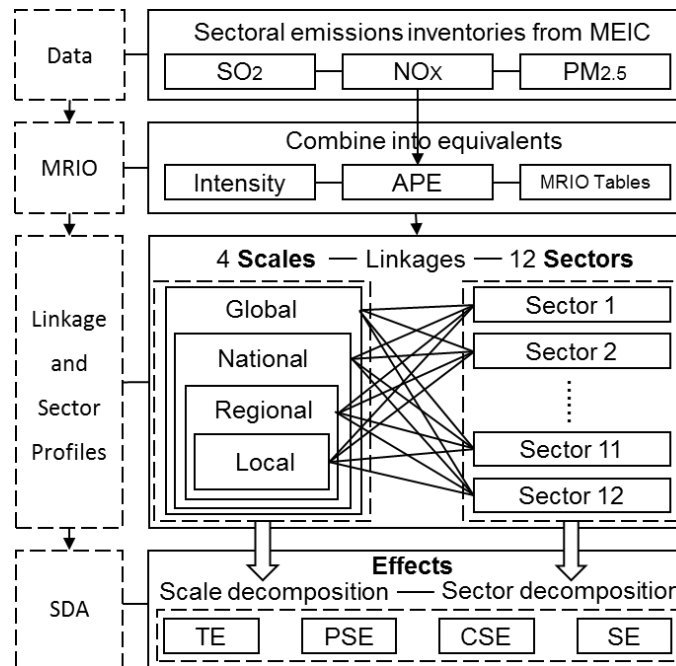
124 For the megaregion level, this study adopted the Yangtze River Delta (YRD) as a
125 case. The YRD has pioneered China's opening up policy thanks to its local advantages
126 and the support of governmental policies. The YRD fosters the largest city cluster
127 nationwide, accounting for 20.4% of the national gross domestic product (GDP) and
128 37.3% of China's exports in 2017 (NBS, 2018). The YRD also serves as a portal
129 connecting the overseas market and the inland regions. In addition, two regional and
130 national development plans intersect in the YRD, namely, the Belt and Road Initiative
131 and the Yangtze River Economic Belt (NDRC, 2016). Therefore, compared with the
132 Beijing-Tianjin-Hebei region and the Pearl River Delta region, the YRD has more links
133 with overseas and inland regions. Nevertheless, rapid economic growth and
134 urbanization make the YRD one of the largest emitters in China and exposes it to a high
135 risk of environmental degradation (Li et al., 2018b; Meng et al., 2019), resulting in the
136 YRD region being one of the most seriously polluted metropolitan regions in China
137 (Liu et al., 2017; Cheng et al., 2019), and industry plays the biggest part in the problem
138 (Zheng et al., 2016). Furthermore, there are large spatial variations in pollution
139 emissions within the YRD region (Cheng et al., 2019). Energy intensity and energy
140 structure were identified as the two main drivers to mitigate emissions in the YRD
141 region (Xu et al., 2017; Zhu et al., 2017). It is worth noting that one of the limitations
142 of previous studies is that they considered the YRD as a static economy, ignoring its
143 strong external economic linkages. Recently, interprovincial air pollution transfer in the
144 YRD has received increasing attention, such as in the electricity sector (Li et al., 2018),
145 but whole-sector and multiscale research is still urgently needed to form an integrated
146 scheme to meet the sustainable targets in the YRD region. The government has been
147 aware of severe environmental problems and has implemented measures to address
148 these challenges (Yang et al., 2015), but there is still much to be done to completely
149 clean the polluted environment (Yang et al., 2019b). The "Ten Measures for the
150 Prevention and Control of Atmospheric Pollution" released by China's State Council in
151 2013 proposed that the treatment of environmental pollution required integrated
152 regional governance, and the "Ten Measures" established a joint control mechanism in
153 Beijing-Tianjin-Hebei, the YRD, and the Pearl River Delta region. Therefore, the YRD
154 region provides an experimental site for environmental pollution control under multiple
155 economic linkages.

156 Overall, this study aimed to develop a four-scale analytical framework to analyze
157 regional export-related pollution problems in the YRD and propose regional emission

158 reduction policy recommendations based on a decomposition analysis of scale and
 159 sectoral EEE shifts. SO₂, NO_x and PM_{2.5} are the main air pollutants (Zhao, et al., 2016a)
 160 and the key prevention and control objectives in China (China State Council, 2013), so
 161 they were selected as emission equivalents in this study. The multiregional input-output
 162 (MRIO) tables of 2007, 2010 and 2012 for 30 provinces (excluding Tibet, Hong Kong,
 163 Macau and Taiwan due to data limitations) and 30 economic sectors were analyzed. The
 164 objectives of this study are to 1) analyze the scale and sectoral characteristics of EEE
 165 in four linkages over time; 2) identify the determinants of scale and sectoral EEE shifts
 166 in the four linkages by employing structural decomposition analysis (SDA); and 3)
 167 propose specific recommendations for regional pollution reduction based on the results
 168 of the four-scale framework.

169 2 Materials and methods

170 This study constructed a four-scale research framework to track the sources of
 171 EEE in the YRD, connecting EEE linkages at multiple scales and between multiple
 172 sectors based on MIRO tables. SDA was applied to decompose the EEE shifts across
 173 scales and sectors (Fig. 1).



174

175 Fig. 1 Research framework of this study. MEIC is a multiscale emission inventory
 176 model; MRIO is a multiregional input-output analysis; APE is atmospheric pollutant
 177 equivalents; SDA is a structural decomposition analysis; *TE* is the technology effect;
 178 *PSE* is the production structure effect; *CSE* is the consumption structure effect; and
 179 *SE* is the scale effect.

180 2.1 Data on production-based pollution emissions

181 Sectoral emission inventories in 2007, 2010, and 2012 in Shanghai, Jiangsu, and
182 Zhejiang in the YRD region were obtained from the China Multiscale Emission
183 Inventory Model (MEIC) database developed and managed by Tsinghua University,
184 China (<http://www.meicmodel.org/>). The MEIC is a bottom-up emission inventory
185 model that covers more than 700 anthropogenic emission sources (Li et al., 2014; Li et
186 al., 2017; Liu et al., 2015). Emission sources are classified based on sector, fuel/product,
187 combustion/process technology, and end-of-pipe control technology. The emission data
188 were mapped to 30 sectors defined in the MRIO model (Zhao et al., 2015).

189 To measure the comprehensive effect of various atmospheric pollutants, this study
190 adopted the “*pollutant equivalent*” method proposed by China’s Ministry of Ecology
191 and Environment, considering the impact on ecological systems, toxicity to organisms
192 and technical feasibility of removing each pollutant (Yang and Wang, 1998). Three
193 main types of air pollutants, SO₂, NO_x, and PM_{2.5}, were selected from the MEIC
194 inventory, and these three pollutants were combined into a new parameter called
195 atmospheric pollutant equivalents (APE). Based on China’s official documents about
196 the pollution charge schedule (SDPC et al., 2003), the conversion coefficients of SO₂,
197 NO_x, and PM_{2.5} to APE are 0.95, 0.95 and 4, respectively, which means that 1 kg APE
198 is equal to 0.95 kg SO₂, 0.95 kg NO_x and 4 kg PM_{2.5}. This study combined SO₂, NO_x,
199 and PM_{2.5} EEE as follows:

$$199 \quad EEE = \sum_{k=1}^n EEE_i / R_k \quad (1)$$

200 where R_k represents the conversion coefficient between different pollutants k and
201 the equivalents.

202 2.2 Multiregional input-output model (MRIO)

203 The socioeconomic and environmental effects of products and services include
204 direct and indirect effects. The input-output model established by Leontief (1974)
205 explains the relationship between sectors and regions, and it has been widely used to
206 track the indirect environmental impacts caused by upstream production. Based on
207 China’s MRIO tables in 2007 and 2010 compiled by Liu et al. (2012; 2014) and in 2012
208 compiled by China Emission Accounts and Datasets (Mi et al., 2017), this study
209 extracted key information and compiled the YRD input-output table. The YRD three-

210 zone model contains detailed information on 30 interprovincial trade and international
 211 export sectors.

212 Table A1 shows the model structure. The balance of money flow in each row is
 213 calculated as follows (Leontief, 1974):

$$\sum_{r=1}^3 \sum_{j=1}^{30} Z_{ij}^{rs} + \sum_{s=1}^{28} y_i^{rs} = x_i^r \quad (2)$$

214 where Z_{ij}^{rs} represents the demand of sector j in province s for sector i in province
 215 r , which is the intermediate input; y_i^{rs} represents the production in sector i in province
 216 r and final consumption in province s ; and x_i^r represents the total output of sector i in
 217 province r ;

$$a_{ij}^{rs} = Z_{ij}^{rs} / x_{ij}^s \quad (3)$$

218 where a_{ij}^{rs} represents the direct consumption coefficient of the unit production of
 219 sector j in province s produced by sector i in province r .

220 Equations 2 and 3 are combined to form Equation 4:

$$Ax + y = x \quad (4)$$

221 where Ax represents $\sum_{r=1}^3 \sum_{j=1}^{30} a_{ij}^{rs} x_{ij}^s$, y represents y_i^{rs} , and x represents x_i^r .

222 Equation 4 is converted into total output as follows:

$$x = (I - A)^{-1} y \quad (5)$$

223 where $(I - A)^{-1}$ is the Leontief inverse matrix, which means that producing a unit of
 224 sector j 's final product requires the sum of one unit product of the sector and the
 225 intermediate products of all other sectors. I represents the identity matrix, and A is the
 226 matrix of a_{ij}^{rs} . By calculating the emission intensity of each region, EEE is calculated
 227 as follows (Zhang et al., 2018a):

$$EEE = Fx \quad (6)$$

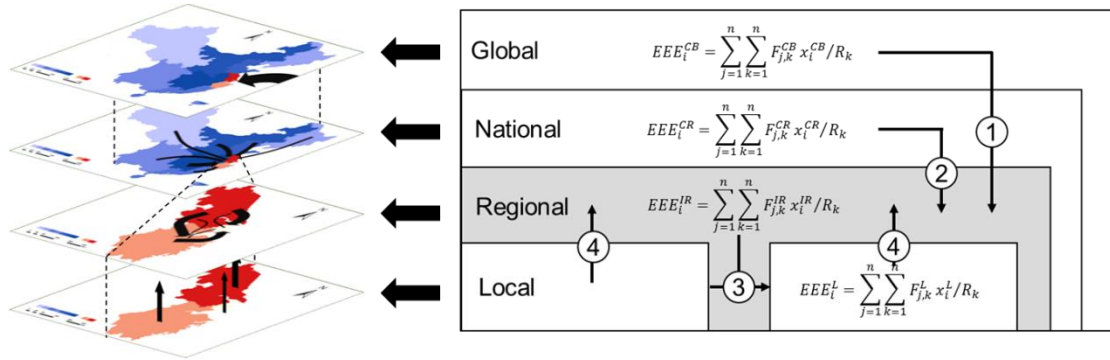
$$EEE = F(I - A)^{-1} y \quad (7)$$

228 where F is the discharge intensity of the exit.

229 2.3 Multi EEE linkage analytical framework based on the region

230 Environmental pollution in an open economic area is often affected on multiple
 231 scales (Mao and He, 2017). Studies have found that an open region's embodied
 232 emissions come from four linkages: 1) cross-border (Liu and Wang, 2015), 2) cross-

233 regional (Zhang et al., 2018b), 3) intraregional (Zhao, et al., 2016a), and 4) local
 234 (Zhong et al., 2017). In this study, an analytical framework of regional embodied
 235 emissions was established based on the calculation of EEE in four export linkages
 236 related to the region. These four linkages correspond to the four scales of EEE : global,
 237 national, regional and local (Fig. 2). In our study, the four linkages are defined as
 238 follows: the first linkage from the global scale refers to the three provinces (Jiangsu,
 239 Zhejiang, and Shanghai) in the YRD as a whole, which produce embodied emissions
 240 through international trade. The second linkage from the domestic scale refers to the
 241 embodied emissions produced by the three provinces in the YRD as a whole and
 242 exported to other provinces in China (except Hong Kong, Macao, Taiwan and Tibet due
 243 to data limitations). The third linkage from the regional scale refers to the embodied
 244 emissions produced by intraregional exports among local areas within the YRD region.
 245 The fourth linkage at the local level refers to the embodied emissions produced by local
 246 production and consumption.



247
 248 Fig. 2 Four-level analytical framework of EEE based on region, where ① EEE_i^{CB}
 249 represents EEE based on the cross-border linkage, ② EEE_i^{CR} represents EEE based
 250 on the cross-regional linkage, ③ EEE_i^{IR} represents EEE based on the intraregional
 251 linkage, and ④ EEE_i^L represents EEE based on the local linkage.

252

253 2.4 Structural decomposition analysis

254 An SDA of emission equivalents embodied in trade can provide further insights
 255 into the factors contributing to the changes in embodied emissions (Xu and
 256 Dietzenbacher, 2014). Such an approach has been used in previous studies (Lan et al.,
 257 2016; Mi et al., 2018; Zhao, et al., 2016b). To quantify the forces driving the change in
 258 EEE , Equation 7 can be broken down into Equation 8 as follows:

$$EEE = F (I - A)^{-1} \frac{y}{x_i^r} x_i^r = TE \cdot PSE \cdot CSE \cdot SE \quad (8)$$

259 where *TE* represents the technology effect; *PSE* represents the production
 260 structure effect; *CSE* represents the consumption structure effect; and *SE* represents
 261 the scale effect. The environmental effects of trade depend mainly on the overall ratio
 262 of the scale, structure and technological effects (Antweiler et al., 2001). A region's
 263 emissions depend on its position and participation level in supply chains (Meng et al.,
 264 2013), while the technical and structural effects of exports are the main factors causing
 265 changes in *EEE* (Duan and Jiang, 2017).

266 The bipolar decomposition method (Dietzenbacher and Los, 1998; Meng et al.,
 267 2018) is used as an approximation of the average of all $n!$ decompositions. The
 268 influencing factors of *EEE* are decomposed as follows:

$$\Delta EEE = f(\Delta TE) + f(\Delta PSE) + f(\Delta CSE) + f(\Delta SE) \quad (9)$$

$$f(\Delta TE) = 1/2[\Delta TE \cdot PSE(0) \cdot CSE(0) \cdot SE(0) + \Delta TE \cdot PSE(1) \cdot CSE(1) \cdot SE(1)] \quad (10)$$

$$f(\Delta PSE) = 1/2[TE(1) \cdot \Delta PSE \cdot CSE(0) \cdot SE(0) + TE(0) \cdot \Delta PSE \cdot CSE(1) \cdot SE(1)] \quad (11)$$

$$f(\Delta CSE) = 1/2[TE(1) \cdot PSE(1) \cdot \Delta CSE \cdot SE(0) + TE(0) \cdot PSE(0) \cdot \Delta CSE \cdot SE(1)] \quad (12)$$

$$f(\Delta SE) = 1/2[TE(1) \cdot PSE(1) \cdot CSE(1) \cdot \Delta SE + TE(0) \cdot PSE(0) \cdot CSE(0) \cdot \Delta SE] \quad (13)$$

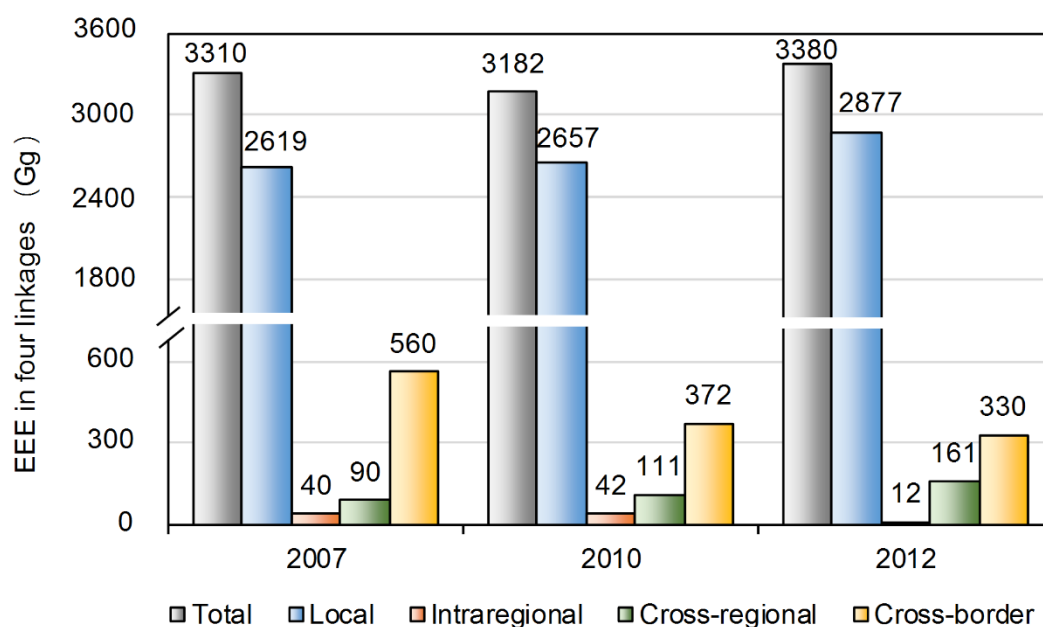
269 **3 Results**

270 Based on the established four-level analytical framework, this study characterized
 271 the spatial and sectoral changes of *EEE* in the YRD region and identified the key
 272 linkages and sectors affecting *EEE* changes. To explore the causes of these shifts, the
 273 four linkages were decomposed by SDA. To propose more specific emission reduction
 274 measures, the key sectors were also decomposed by SDA.

275 **3.1 EEE profiles in the YRD region in the four linkages**

276 Figure 3 shows the *EEE* changes in the entire region and the four linkages. The
 277 total *EEE* in the YRD region experienced a decreasing and then an increasing trend
 278 from 2007 to 2012, with a peak at 3,380 gigagrams (Gg) in 2012 (Fig. 3). The regional
 279 *EEE* was mainly influenced by local and cross-border linkages. The local *EEE*
 280 experienced sustained growth, peaking at 2,877 Gg in 2012. The proportion of local

281 EEE in total EEE in the region also increased, accounting for 85.1% in 2012. The cross-
 282 border EEE linkage decreased by 41.0% from 2007 to 2012, contributing only 9.8% to
 283 the total EEE in the region in 2012. However, the EEE changes in the intraregional and
 284 cross-regional linkages were not as obvious as the changes in the other two linkages.
 285 Similar to the cross-border linkage, intraregional EEE decreased by more than 70.1%
 286 from 2007 to 2012. In contrast, cross-regional EEE increased by nearly 78.7% between
 287 2007 and 2012, accounting for nearly 4.8% of the total EEE in 2012. In general, from
 288 the perspective of the EEE changes in the four linkages, local linkages continued to
 289 have the highest proportions. The impact of cross-border and intraregional linkages on
 290 the regional environment decreased, while the influence of cross-regional linkage on
 291 the regional environment increased.

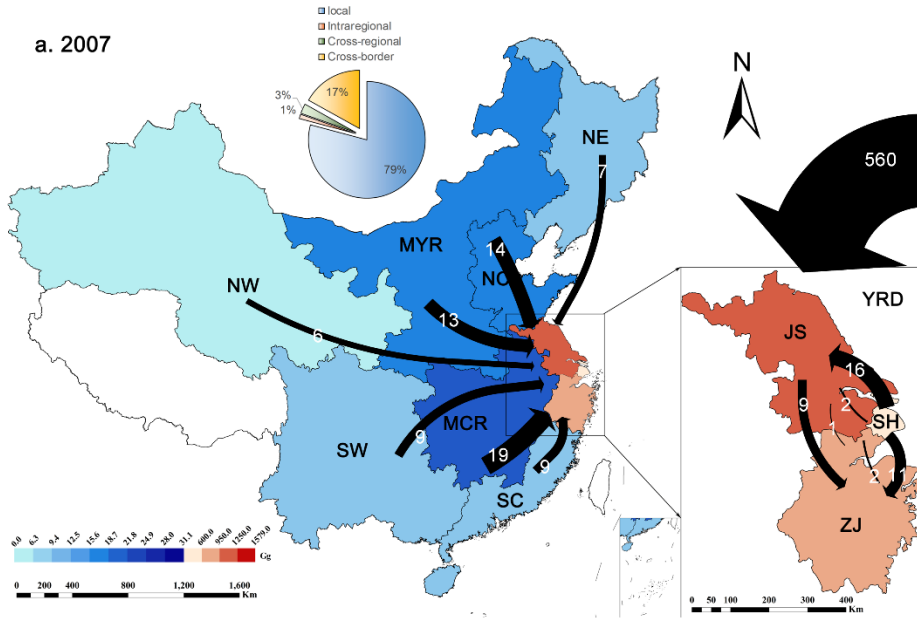


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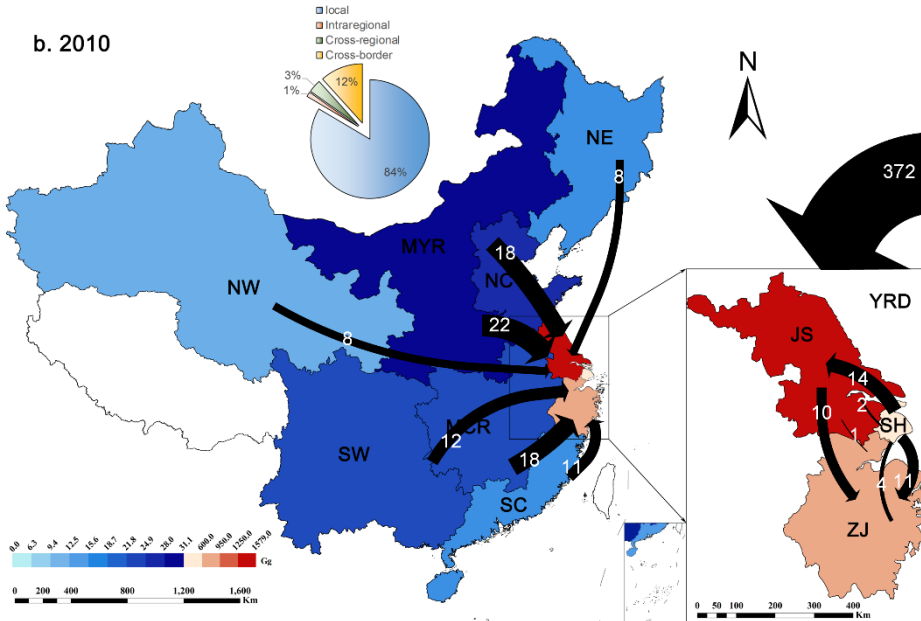
Fig. 3 EEE changes in the YRD based on four linkages

a. 2007

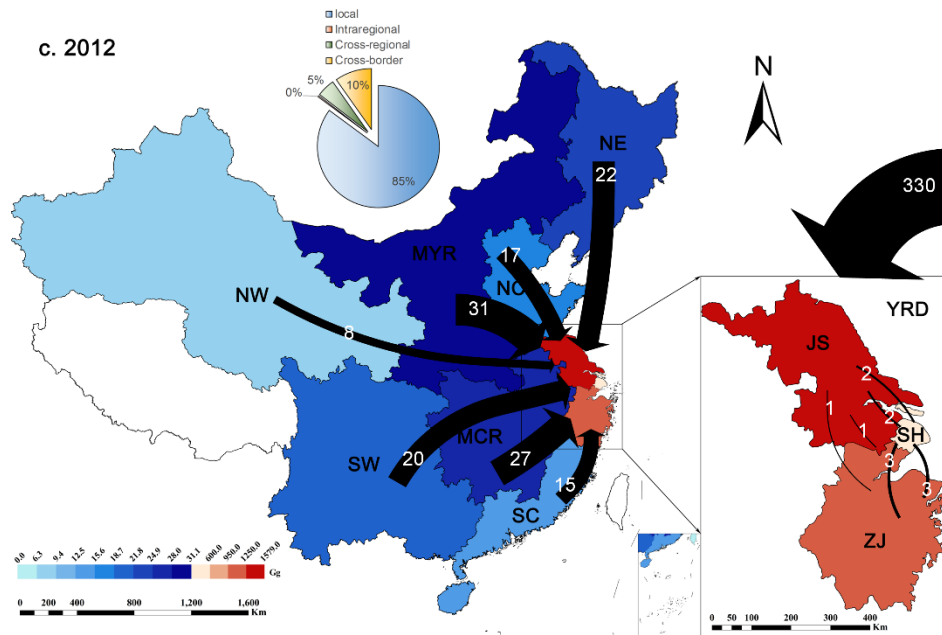


294

b. 2010



295



296

297

298 Fig. 4 Spatiotemporal changes in EEE in the YRD. EEE in the YRD region in 2007 (a),
 299 2010 (b), and 2012 (c). The thickness and number of the arrows represent the amount
 300 of EEE transferred. SH is Shanghai municipality; JS is Jiangsu Province; ZJ is Zhejiang
 301 Province; NE is Northeast China; NC is northern coastal China; SC is southern coastal
 302 China; MYR is middle of the Yellow River; MCR is middle of the Yangtze River; NW
 303 is Northwest China; SW is Southwest China; and YRD is the Yangtze River Delta.

304

305 From the perspective of the local linkage, the local EEE in the YRD region
 306 generally experienced an increasing trend, with spatial variations between the three
 307 provinces (Fig. 4). The local EEE in Shanghai decreased by 26.3% from 2007 to 2012,
 308 accounting for only 11.1% of the YRD's local EEE in 2012. In contrast, the local EEE
 309 in Jiangsu gradually increased, contributing 54.9% to the YRD's local EEE in 2012.
 310 During the same period, the local EEE in Zhejiang experienced an increase and then a
 311 decrease, accounting for 34.1% of the YRD's local EEE in 2012.

312

313 The intraregional EEE linkage in the YRD showed a gradual decreasing trend (Fig.
 314 4). In particular, the intraregional EEE from Jiangsu and Zhejiang declined markedly,
 315 by 76.2% and 80.4%, respectively, from 2007 to 2012. In terms of intraregional linkage,
 316 Jiangsu experienced more intraregional EEE from the other two provinces, while the
 EEE in Shanghai and Zhejiang gradually lessened.

317

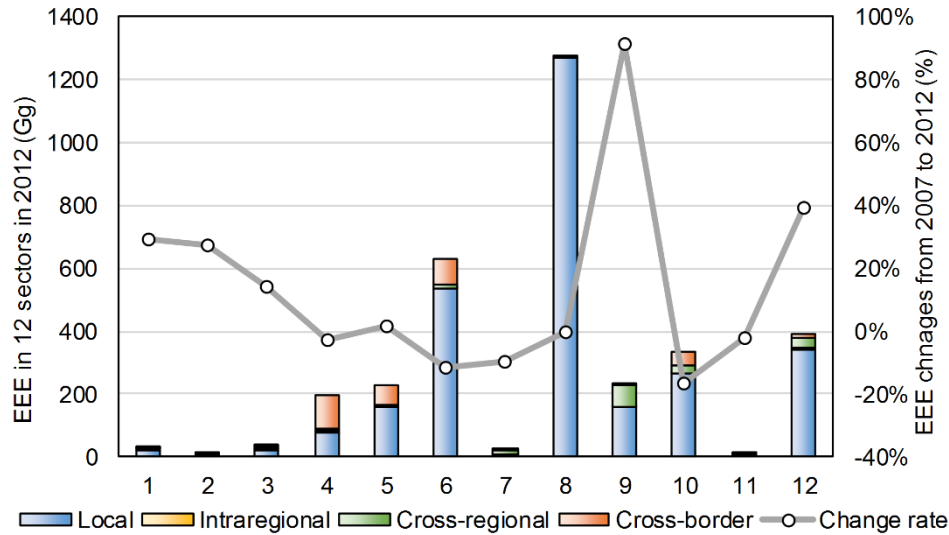
318 The regional EEE across the YRD caused by the cross-regional linkage continued
 to increase over the period due to contributions from all regions across China (Fig. 4).

319 The most marked increase appeared in Northeast China, the middle of the Yellow River
320 and Southwest China, which saw increases of 218.6%, 144.8% and 113.1%,
321 respectively, during the period of 2007-2012. Slow increases occurred in southern
322 coastal China, the middle of the Yangtze River, Northwestern China, and northern
323 coastal China, where EEE increased by 68.3%, 44.1% 31.3%, and 22.8%, respectively.
324 The geographic center of gravity of the cross-regional EEE linkage moved 127
325 kilometers to the northeast between 2007 and 2012.

326 Regarding the cross-border EEE linkage in the YRD region, international exports
327 in the YRD region gradually reduced between 2007 and 2012. Zhejiang and Shanghai
328 had larger decreases (60.0% and 55.7%), while Jiangsu had a smaller reduction (33.9%).

329 **3.2 Sector-specific EEE in the YRD**

330 The analyses of the EEE of different sectors at four scales can identify the effects
331 of each sector on the EEE in the YRD region (Fig. 5). In terms of the overall EEE
332 situation in the YRD region, sector 8 (energy industry) had the largest EEE. This sector
333 experienced a decrease and then an increase from 2007 to 2012, accounting for 37.5%
334 of the EEE in the YRD region in 2012 and the largest proportion of EEE at the local
335 level (44.0%). The environmental impact of sector 9 (construction) on the YRD region
336 had the fastest growth rate, growing 91.5% from 2007 to 2012, and it was a key sector
337 in the cross-regional linkage, accounting for 42.7%. Sector 10 (transportation) had the
338 largest rate of decrease (-16.8%), while sector 12 (other services) had the largest
339 increase (+110.2 Gg) and contributed the largest proportion at the intraregional level
340 (34.3%). Sector 6 (metal and nonmetal products) had the largest reduction in EEE (-
341 83.1 Gg), and it made a marked contribution to EEE in the YRD region, accounting for
342 18.6% of the EEE in 2012. Sector 4 (light industry products) accounted for most of the
343 EEE due to cross-border linkage (32.8%).



344

345 Fig. 5 EEE in 12 sectors at four levels in 2012 and changes in EEE by sector from 2007 to 2012.

346 Numbers 1 to 12 represent agricultural products, mining products, foods, light industry products,

347 chemical products, metal and nonmetal products, equipment, energy, construction, transportation,

348 wholesale and retailing, and other services, respectively. See appendix Table A2 for more details.

349

350 EEE had obvious sector-specific characteristics at the four scales. The change in

351 the total EEE in the YRD region from 2007 to 2012 was mainly affected by the local

352 and cross-border linkages of EEE (Fig. 6). The increase in local EEE was mainly caused

353 by labor-intensive industries, such as sector 4 (light industry products) (+35.1 Gg),

354 sector 9 (construction) (+47.5 Gg), and sector 12 (other services) (+91.2 Gg), and by

355 capital-intensive industries, such as sector 5 (chemical products) (+16.5 Gg), sector 8

356 (energy) (+42.9 Gg), and sector 10 (transportation) (+52.4 Gg). The decrease in the

357 cross-border EEE linkage was mainly due to the decline in sector 10 (transportation),

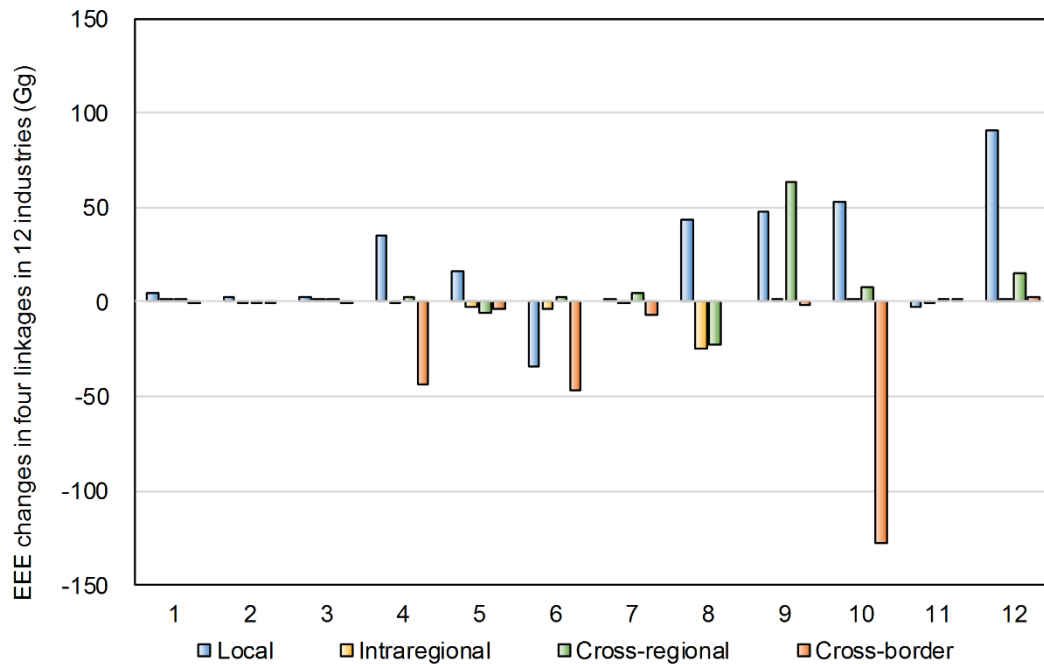
358 sector 4 (light industry products), and sector 6 (metal and nonmetal products). Among

359 these, sector 10 (transportation) saw the largest reduction (-128.3 Gg). In contrast, the

360 intraregional and cross-regional EEE linkages experienced minor changes. The increase

361 in cross-regional EEE was mainly caused by sector 9 (construction), while the decrease

362 in intraregional linkage was primarily caused by sector 8 (energy).



363

364 Fig. 6 Changes in EEE at four levels in 12 sectors from 2007 to 2012. Numbers 1 to 12 represent
 365 agricultural products, mining products, foods, light industry products, chemical products, metal and
 366 nonmetal products, equipment, energy, construction, transportation, wholesale and retailing, and
 367 other services, respectively. See appendix Table A2 for more details.

368 3.3 The restructuring of EEE in the YRD region

369 To analyze the influencing factors of EEE in the YRD region at the four scales from
 370 2007 to 2012, SDA was conducted to deconstruct the factors into four types of effects:
 371 technical effect (*TE*), production structure effect (*PSE*), consumption structure effect
 372 (*CSE*) and scale effect (*SE*).

373 The local EEE in the YRD region experienced a continuous increase (Fig. 7a),
 374 growing by 1.4% from 2007 to 2010 and by 8.3% from 2010 to 2012. The local EEE
 375 was mainly affected by *TE* and *SE*. Although the increase brought by *SE* weakened
 376 from 52.9% to 33.3%, *TE* did not show an obvious effect (decreasing from 44.3% to
 377 19.4%), with the consequence being the continuous increase in local EEE in 2012.

378 The intraregional EEE linkage in the YRD region experienced an increase of 3.0%
 379 from 2007 to 2010 and a significant decrease of 71.0% from 2010 to 2012 (Fig. 7b).
 380 After 2010, the main reason for the decrease in intraregional EEE linkage was the
 381 marked reduction in *CSE* (76.2%) in the region. Obvious changes in the consumption
 382 structure have appeared among cities in the YRD region.

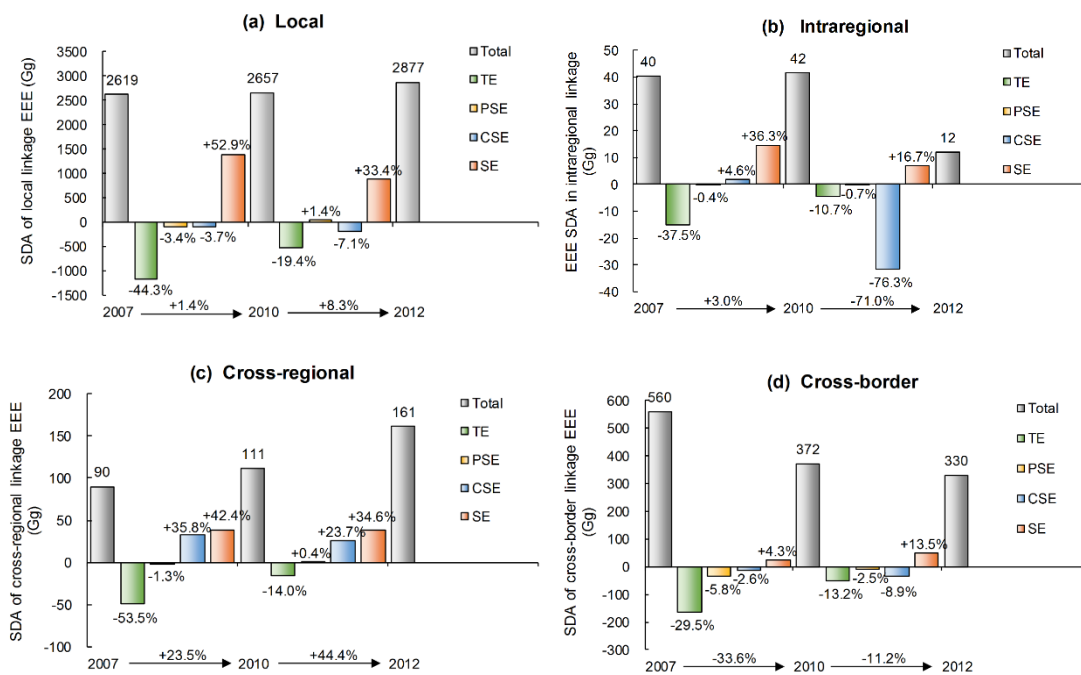
383 The cross-regional EEE linkage continued to increase (Fig. 7c) by a rate of 23.5%
 384 from 2007 to 2010 and 44.7% after 2010. The continuous increase in cross-regional

385 EEE was affected by *TE*, *CSE* and *SE*, and the main reason for the continuous increase
 386 was the decrease in *TE*. From 2007 to 2010, the decrease in *TE* was not balanced by the
 387 increase in *CSE* and *SE*. After 2010, *TE* decreased from 53.3% to 14.4%. The YRD
 388 region was one of the most technologically advanced regions in China. Other less-
 389 developed regions, for example, inland China, increasingly relied on technology
 390 transfer from the YRD region, leading to the increase in cross-regional EEE.

391 The cross-border EEE linkage in the YRD region gradually decreased due to the
 392 influence of the international economic situation (Fig. 7d), while the reasons for the
 393 reduction in cross-border EEE linkage varied. From 2007 to 2012, EEE at this level
 394 decreased by 33.6%, mainly due to the contribution of *TE* and *PSE*. From 2010 to 2012,
 395 the reduction declined to 11.2%. During this period, *TE* decreased from 29.5% to 13.2%,
 396 while *CSE* grew from 2.5% to 8.9%. Thus, the reduction in cross-border EEE linkage
 397 depended on technology upgrading and the optimization of the production structure of
 398 export products.

399

400



401

402

403 Fig. 7 Structural decomposition analysis (SDA) of EEE in the four linkages from 2007
 404 to 2012: (a) local EEE, (b) intraregional EEE, (c) cross-regional EEE, and (d) cross-
 405 border EEE. *TE* means technical effect, *PSE* means production structure effect, *CSE*
 406 means consumption structure effect and *SE* means scale effect.

407

408 Six sectors were selected for further decomposition. These sectors contributed to
409 the vast majority (90.1%) of the EEE in the YRD region (Fig. 5); among them, sectors
410 8 and 6 accounted for 37.5% and 18.6%, respectively. Furthermore, sectors 12 and 9
411 experienced the largest increase (+110.2 Gg and +109.5 Gg), while sectors 6 and 10
412 saw the largest decrease (-83.1 Gg and -63.4 Gg) (Fig. 6). Therefore, these sectors,
413 which include capital-intensive sectors (6, 8, 9 and 10) and labor-intensive sectors (4
414 and 12), had a crucial impact on EEE transfer at the four scales.

415 As shown in Figure 6, sector 4 (light industry) mainly affected the increase in the
416 local EEE linkage and the decrease in the cross-border EEE linkage in the YRD. In
417 addition, sector 4 had the largest proportion of cross-border EEE linkage. From the
418 SDA results (Fig. 8a), the decline in sector 4 in 2007-2010 was mainly due to the large
419 decline in *TE* in the local and cross-border linkages, while the increase from 2010 to
420 2012 was mainly due to the *SE* formed by local and cross-border linkages. In addition,
421 *TE* lost its decreasing effect in the cross-border linkage in 2010-2012. Obviously, the
422 local and cross-border linkages were the key linkages of sector 4 in the YRD region.

423 Sector 6 (metal and nonmetal products) saw the largest reduction in EEE in the
424 YRD region, decreasing by 83.1 Gg from 2007 to 2012 (Fig. 8b). Local and cross-
425 border linkages were the key linkages affecting the change in this sector. The
426 accelerated decline in 2010-2012 was mainly due to the shift from a local production
427 structure to a cross-border consumption structure. In general, the reduction in pollution
428 emissions in this sector was more dependent on local and cross-border production and
429 consumption restructuring.

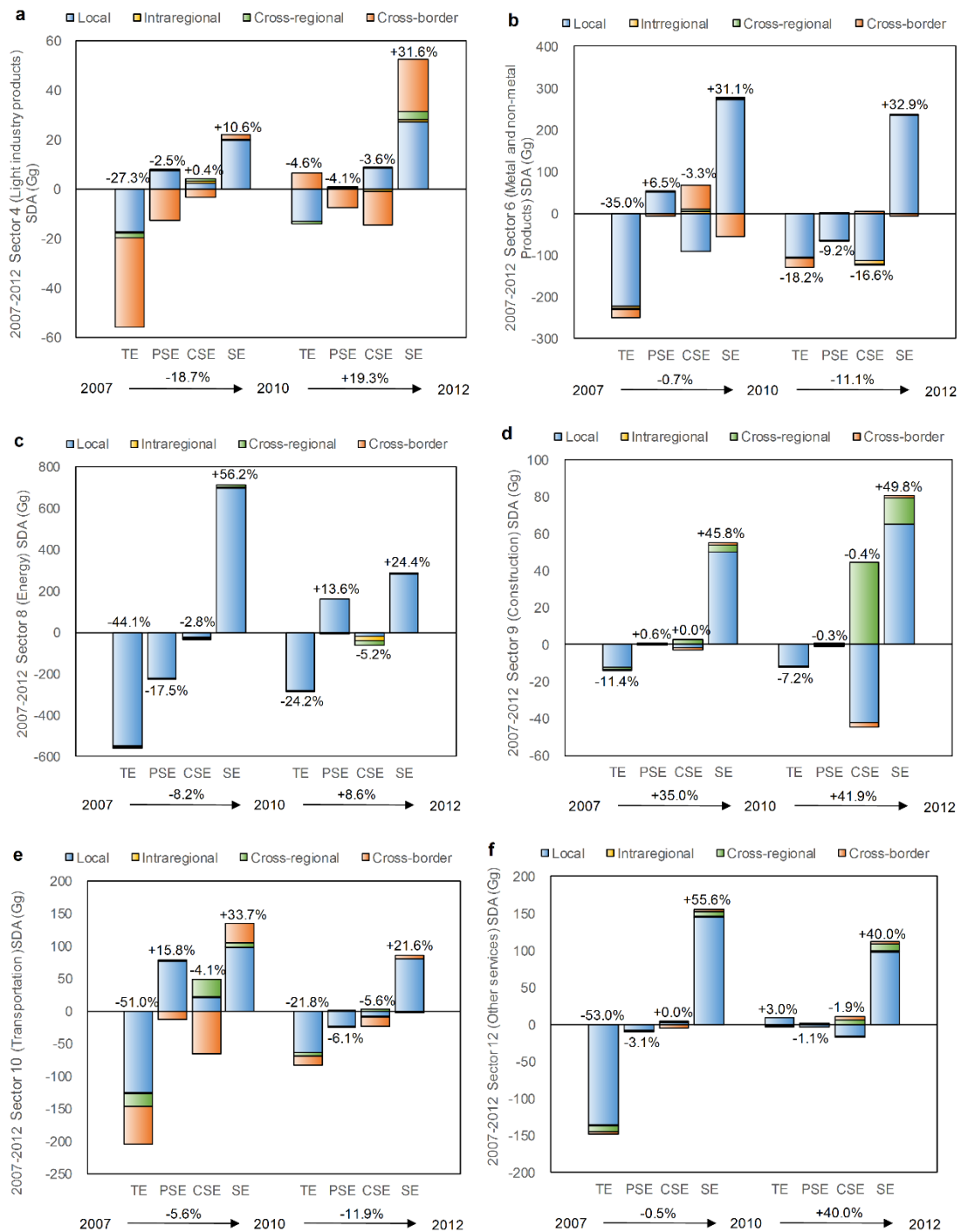
430 Sector 8 (energy) had the largest EEE ratio (37.5%) in the YRD. As the sector with
431 the largest proportion of local EEE (44.0%), sector 8 was mainly affected by the local
432 linkage (Fig. 8c). The EEE of sector 8 first experienced a decreasing and then an
433 increasing trend, mainly because of the change in *TE* and *PSE* for the local linkage.

434 With its continuous increase (Fig. 8d), sector 9 (construction) had the largest rate
435 of increase in EEE from 2007 to 2012 (91.5%) and the largest proportion of cross-
436 regional EEE linkage (42.7%). This sector was mainly affected by local and cross-
437 regional linkages. After 2010, the growth rate of EEE in sector 9 increased more rapidly
438 because of the increase in *CSE* and *SE* at the cross-regional scale. In addition, local
439 linkages always maintained a high *SE*, which was also a reason for the continued
440 increase in this sector.

441 With a continuous decrease (Fig. 8e), sector 10 (transportation) had the largest
 442 reduction rate (16.8%) in 2007-2012, mainly due to the reduced technical advantage of
 443 local, cross-regional and cross-border linkages. The increasing decline was mainly
 444 caused by *PSE* (local linkage) and *SE* (cross-border linkage).

445 Sector 12 (other services) had the largest increase in EEE (110.2 Gg) and the
 446 largest proportion of EEE at the intraregional scale (34.3%) in the YRD region (Fig.
 447 8f). This sector was mainly affected by the loss of *TE* in the local linkage.

448



449

450

451

452 Fig. 8 Structural decomposition analysis (SDA) results for selected sectors from 2007
453 to 2012. (a) Sector 4 (light industry products), (b) sector 6 (metal and nonmetal
454 products), (c) sector 8 (energy), (d) sector 9 (construction), (e) sector 10 (transportation),
455 and (f) sector 12 (other services). *TE* means technical effect; *PSE* means production
456 structure effect; *CSE* means consumption structure effect; and *SE* means scale effect.
457

458 **4 Discussion**

459 The MSIO model including intraregional linkages can improve the existing
460 multiscale analytical framework (Chen et al., 2013; Shao et al., 2017). Despite the small
461 EEE within the intraregional linkage in the YRD region, our results show a clear trend
462 of a decrease in intraregional linkage accompanied by an increase in cross-regional
463 linkages. These findings not only expanded our analyses of the scale and sectoral
464 dynamics but also increased our understanding of the region's air pollution and its
465 possible causes.

466 In particular, the developed MSIO model incorporating intraregional linkage
467 revealed the profound imbalance in the development process of regional integration,
468 reflected in both economic development and pollution emissions. In terms of local EEE
469 linkage in the YRD, the local EEE ratios in Shanghai, Jiangsu and Zhejiang changed
470 from 16% to 11%, 48% to 55%, and 36% to 34%, respectively, from 2007 to 2012 (Fig.
471 4). The proportion of GDP of the three provinces within the YRD was 18%, 50%, and
472 32%, respectively, in 2012 (NBS, 2013). It is clear that the development paths of
473 Shanghai and Zhejiang were greener than that of Jiangsu. These results supported
474 previous research findings that international trade can promote global economic growth
475 but may also exacerbate regional imbalances in internal trade (Daumal, 2013; Zhong et
476 al., 2018). This feature is particularly marked in developing countries (Rivas, 2007).
477 Not only the YRD region but also the developed Beijing–Tianjin–Hebei region (Zhao,
478 et al., 2016a) and the Pearl River Delta region (Zheng et al., 2012) face this
479 development dilemma.

480 Based on the analytical advantages of the multiscale model constructed in this study,
481 the dynamic performance of the pollution haven hypothesis in the YRD region can be
482 analyzed more accurately and with more details. Judging from the increase in the total
483 amount of embodied pollution in the YRD region, the pollution haven effect increased
484 in the YRD region from 2007 to 2012. However, the pollution haven effect was different

485 from various directions outside the YRD region. In other words, the major sources of
486 embodied pollution gradually shifted among linkages. Considering the declines in
487 sector 10 (transportation), sector 4 (light industry products), and sector 6 (metal and
488 nonmetal products), the YRD gradually escaped from the dilemma of the pollution
489 haven hypothesis from cross-border linkage. As mentioned in previous research (Xu
490 and Song, 2000), due to their comparative advantages, some labor-intensive industries,
491 such as light industry, have shifted from China's east coast to Southeast Asia. Because
492 of the increase in sector 9 (construction) exporting from the YRD to other regions in
493 China, the pollution haven effect from cross-regional linkage was strengthened during
494 the period of 2007-2012. The enhanced cross-regional linkage of the YRD with other
495 regions showed that the inland regions still had a greater dependence on the coastal
496 regions. This result was consistent with Mi and his colleagues' (2017) finding that the
497 carbon emission transfer from China's coast to the inland regions has started to reverse.
498 Therefore, the transformation and upgrade of the economy in coastal areas have not
499 completely transferred the pollution out. The decrease in the intraregional EEE linkage
500 indicates that regional integration in the YRD is oriented toward both the national and
501 international markets. The YRD region tends to be more outward than inward looking
502 (Wu et al., 2017).

503 In general, the YRD region is still in a transition period and is suffering from
504 increasing environmental pollution due to production and consumption internally and
505 in other regions in China (Yang et al., 2012b). For sustainable development, it is vital
506 to find the key linkages, sectors and factors causing regional environmental pollution
507 (Lu et al., 2015). With the four-level analytical framework, this study effectively
508 identified the key linkages, sectors and factors causing air pollution in the YRD. Based
509 on the results, the following recommendations are proposed. First, more investment is
510 needed from provincial governments to promote local technological innovation (Duan
511 and Jiang, 2017; Zhu et al., 2014). Specifically, more technology innovation is urgently
512 required in the key sectors, including sector 4 (light industry), sector 8 (energy), sector
513 9 (construction), sector 10 (transportation) and sector 12 (other services). Second, it is
514 necessary to strengthen pollution taxation (Chen et al., 2015; Yang 2014), especially for
515 sectors oriented toward the local scale, such as sector 4 (light industry) and sector 9
516 (construction). Third, further industry restructuring is necessary to reduce the emissions
517 embodied in cross-border linkages (Lin et al., 2014), especially by adjusting the
518 production and consumption structure of sector 4 (light industry) at the cross-border

519 scale. Fourth, for the key export regions of the YRD, such as the middle of the Yellow
520 River and Northeast China, moderate technology transfer could be achieved among
521 regions (Lopez et al., 2019), especially in sector 9 (construction). These
522 recommendations could reduce air pollution in the YRD, other regions in China and
523 even other countries with similar levels of environmental pollution and economic
524 development.

525 Like many studies, this research has some limitations. First, efforts have been made
526 to collect as much data as possible, but the time series is limited to the data available in
527 the MRIO tables. Second, because this study focused on the exploration of the
528 environmental pressures brought by multiple linkages among a region's EEE, it was
529 difficult to explore the impact of the upstream supply chain through imports. However,
530 improving imports in the upstream supply chain could alleviate regional environmental
531 pressures (Chen et al., 2017). Therefore, more studies are needed targeting the upstream
532 supply chain.

533 **5 Conclusion**

534 With worsening air pollution globally, it is important to track the sources of
535 regional air pollutants. A multilevel analytical framework helps analyze and address the
536 embodied emissions problems in a region more comprehensively and with greater detail.
537 This study established a four-level analytical framework (local–intra-regional – cross-
538 regional–cross-border) of regional EEE, revealing that local and cross-border linkages
539 were the two linkages most crucially affecting EEE in the YRD. To effectively reduce
540 regional environmental pollution, it is necessary to detect the key linkages and key
541 sectors with a multiscale model. In the YRD region, local technological investment
542 must be strengthened in key sectors with the largest proportion of EEE and increasing
543 local linkages, including sector 4 (light industry) and sector 8 (energy). To prevent the
544 region from becoming a pollution haven for developed countries, cross-border EEE
545 linkages need to be reduced by adjusting the production and consumption structure of
546 light industry. Cross-regional EEE linkages can be reduced through technology shifts
547 in the construction sector. Additionally, the trends of a decrease in intraregional linkage
548 and an increase in cross-regional linkage suggest that the development of the YRD has
549 tended to be more outward than inward looking, which clearly described the dynamics
550 of pollution emission in the YRD.

551 Compared with the conventional approaches of embodied pollution, the multiscale
552 approach allows for the complexity of one region's economic interdependencies.
553 Moreover, this improved multiscale approach makes it possible to investigate the
554 changing sources of embodied pollution associated with regional development. On this
555 basis, embodied pollution will capture not only the quantitative dynamics but also more
556 sophisticated structural changes. For a region with a high level of openness and
557 economic vitality, this novel multiscale approach is essential for addressing the
558 worsening environmental pollution due to rapid development. The dynamic diagnosis
559 of the emissions embodied in the four linkages indicates that the increasing pollution in
560 the YRD region was dominated by high production demand from the local energy
561 industry, limited local technology innovation, and the dependence of the cross-regional
562 construction industry on consumption. These major findings directly answer the
563 question why the developed YRD region is blocked on in its path to green
564 transformation.

565 The multiscale approach in this study incorporates a new level: the megaregion
566 level. This incorporation is based on a new trend in regional development across the
567 world, where globalization is giving place to regional integration, either globally or
568 locally. Megaregions are playing an increasing role in promoting regional development.
569 The linkages inside and outside the megaregions will further alter the flows of
570 embodied pollutions, which are driven by different determinants. The multiscale
571 approach in this study can identify the internal and external dynamics of economic
572 linkages, indicating that the YRD region gradually transformed from export-oriented
573 growth to endogenous development. Meaningfully, the increase in embodied emissions
574 in the YRD region is accompanied by the weakening of globalization and regional
575 integration. Therefore, this approach is especially meaningful for the core regions
576 within one economy and the transition regions that are shifting from an export-oriented
577 growth model to an endogenous one.

578 **Appendices**

579 Table A1. Region input-output table for the YRD region

	SH	JS	ZJ	Final demand			Interprovincial export	International exports	Total exports
				SH	JS	ZJ	Shanxi ... Xinjiang etc. 27 provinces		
SH	<i>Z</i>			<i>Y</i>			<i>Ex</i>		<i>x</i>
JS									
ZJ									
Value added	<i>v</i>								
Total outputs	<i>x</i> [^]								

580 Note: SH is Shanghai municipality; JS is Jiangsu Province; ZJ is Zhejiang Province

581 Table A2. Sector mapping

Code	Aggregated sectors	30 sectors for Chinese MRIO
1	Agriculture	Agriculture
2	Mining	Coal mining Petroleum and gas Metal mining Nonmetal mining
3	Foods	Food processing and tobaccos
4	Light Industry	Textile Clothing, leather, fur, etc. Wood processing and furnishing Paper making, printing, stationery, etc.
5	Chemicals	Petroleum refining, coking, etc. Chemical industry
6	Metal and Nonmetal Products	Nonmetal products Metallurgy Metal products General and specialist machinery
7	Equipment	Transport equipment Electrical equipment Electronic equipment Instrument and meter Other manufacturing
8	Energy	Electricity and hot water production and supply Gas and water production and supply
9	Construction	Construction
10	Transport	Transport and storage
11	Wholesale and retailing	Wholesale and retailing
12	Other services	Hotel and restaurant Leasing and commercial services Scientific research Other services

583 Table A3. Region classifications of 30 provinces in China*

Abb.	Region	Provinces in the region
NE	Northeast	Liaoning, Jilin, Heilongjiang
NC	North Coast	Beijing, Tianjin, Hebei, Shandong
SC	South Coast	Fujian, Guangdong, Hainan
MYR	Middle of the Yellow River	Shanxi, Inner Mongolia, Henan, Shaanxi
MCR	Middle of the Yangtze River	Anhui, Jiangxi, Hunan, Hubei
SW	Southwest	Chongqing, Sichuan, Yunnan, Guizhou, Guangxi
NW	Northwest	Gansu, Qinghai, Ningxia, Xinjiang
YRD	Yangtze River Delta	Shanghai, Jiangsu, Zhejiang

584 *Hong Kong, Macao and Taiwan were excluded due to data limitation.

585

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