1   **Drivers of fluctuating embodied carbon emissions in international**

2   **services trade**

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19   Summary

20   **Service industries are always considered "green" because of the marginal direct emissions although**
21   **they account for 65% of the world GDP and over 20% of total global trade in 2019. Here, we quantify**
22   **the evolution of carbon emissions embodied in services trade from 2010-2018 and identify the driving**
23   **factors of emission change at the global and regional scales. The annual growth rate of embodied**
24   **emissions exported from the global South (2.0%) is double that of the global North (1.0%), with a**
25   **different trade structure. We further identify three trade patterns of service export in the global**
26   **South based on the bilateral trade partnership and annual growth rate. Three kinds of specific**
27   **emission mitigation policies are proposed based on the characters of services trade and different**
28   **trade structures between different regions. The results provide quantitative evidence currently**
29   **lacking and critical to policy decision making.**

30

31   **Keywords:** CO_2, emissions embodied in trade, services trade, structural decomposition
32   analysis

Introduction

Rapid growth in international trade has resulted in a large portion (more than 20%) of global CO_2 emissions embodied in trade (EET) since 2000[1-3]. A major driver of this result has been the increasing trade in goods and services produced in developing countries and exported to developed countries (so-called South-North trade). As a result, developing countries have generated additional CO_2 emissions to satisfy increased consumption levels in developed countries – in other words, the emissions are redistributed to developing countries due to the shift of the production activities from developed countries. As most carbon emission targets and policies focus on emissions within territorial boundaries without considering the spillover effect described above, they could fail to limit emissions and indeed they could lead to an increase in global emissions[4,5]. Against this backdrop, the role of international trade in carbon transfer has received increasing attention[6-8], with EET becoming a critical component in a national carbon mitigation strategy.

The services trade contributed over 20% to world trade in 2019, up from just 9% in 1970[9]. More specifically, the share of services trade by developing economies has increased by more than 10% since 2005[9], reflecting the growing role developing countries are playing in the evolution of the global services trade. Although the service industries have been always considered green and therefore have attracted only marginal attention in terms of climate change mitigation[10,11], from a consumption perspective, energy consumption and carbon emissions along the services supply chain should be considered[12,13].

Previous studies have looked at the underestimation of energy consumption and carbon emissions in the services industries but have not considered the spillover effect outside the territory[14,15]. Meng et al touched a little on the issue of emissions embodied in services trade but did not separate it from the trade of goods[16]. More recently, studies have analyzed the footprint and bilateral embodied carbon flow of tourism, which has some overlap with services trade, and have concluded that they play an important role in driving global carbon emissions[17,18]. Given the growth of services trade, it is necessary to analyze how changes in both direct and indirect emissions embodied in the services trade and, in particular, what the drivers behind that change are.

This study fills the gap by using the latest CO_2 emissions data from the International Energy Agency (IEA)[19] and multi-regional input-output table (MRIO)[20] to track the change of carbon emissions embodied in the services trade from 2010–2018 (In this study, the services trade is defined as the intermediate and final use offered by the service sectors of an economy to other economies, or international services export). Specifically, our analysis covers 59 regions (58 regions are individual countries) and 35 sectors, among which 19 are service sectors (**See Table S1-S2**). We find that a rapid growth of both trade volume and CO_2 emissions embodied in services trade by 2010-2018 at annual average growth of 4.71% and 1.4%, separately. Although the total volume of the emissions embodied in services trade is smaller that in merchandise trade[21,22], the annual growth rates of both trade volume (4.0%) and the embodied emissions (1.1%) in merchandise trade in 2010-2018 are smaller than services trade. We also explore the drivers behind the change using Structural Decomposition Analysis (SDA)

74   (See Methods). Furthermore, we discuss three main trade patterns of service in the global
75   South and separately analyze their services trade structure and their service supply chains.

Results

Emission change and services trade pattern in 2010-2018

78   Fig 1 presents the change of global services trade and associated trade emissions from 2010
79   to 2018. The volume of trade in services has experienced rapid growth at 4.71% per year.
80   However, emissions embodied in the services trade have only been growing by 3.47% (from
81   2.05Gt-2.35Gt) during 2014-2018, as shown in Fig 1a.

82   We have witnessed the largest growth in services trade. The volume of services trade from
83   developing countries (South) to developed countries (North) has grown 57.7% from 728.6
84   billion US dollars in 2010 to 1148.9 in 2018. The associated embodied emissions in trade have
85   grown 29.2%. The volume of services trade among North-North countries has shown a rapid
86   growth at a rate of 45.3%, but the associated trade emissions have only increased by 8.4%,
87   which means that North-North trade contributed less to the rapid increase of CO_2 emissions
88   embodied in global services trade. The growth of services trade between South-South
89   countries is also significant - an increase by 49.2% from 534.0 US billion dollars in 2010 to
90   805.5 in 2018. Similarly, the volume of services trade among North-South countries has grown
91   on average 36.3% while the embodied emissions of North-South trade have increased by 7.8%.
92   The North-South trade patterns are different during 2010-2014, when the embodied
93   emissions in services trade between developing countries and developed countries decreased
94   slightly except for the case of North-South trade with a positive average annual growth rate
95   of 0.35% (**Figure 1A**).

96   Regarding the types of service exports, we selected a number of countries showing different
97   directions of emissions in Fig 1a, which are based on the amount of the trade volume and the
98   embodied CO_2 emission volume between different countries. The tourism sector is the main
99   source of service exports from the global South. According to the Statistics Department of
100 Vietnam, the number of Japanese visitors has increased sharply by 87.0% from 442.1 thousand
101 people in 2010 to 826.7 in 2018. Therefore, the air transportation and the wholesale trade,
102 which is closely connected to tourism, registered rapid growth of 23.1% and 16.5%,
103 respectively, during 2010-2018 (**Figure 1B**).

104 The professional services trade contributed largely to the North-North trade. Fig 1c shows that
105 services trade between the Netherlands and Germany was dominated by renting and other
106 business services, with an annual growth rate of 8.23% during 2014-2018. In 2018, the
107 Netherlands exported 185 billion US dollars' worth of services with the top services in 2018
108 being other business services (83.9 billion US dollars), showing an increase of 165% compared
109 to 2010 (31.7 billion US dollars). Part of those exports is represented by the trade volume
110 exported to Germany that went up to 8.01 billion US dollars (UN Comtrade). And because the
111 emissions embodied in renting and other business services are relatively low, we find a high

112 growth rate of services trade and a relatively low growth rate of embodied emissions between
113 the Netherlands and Germany, respectively20.7% and 8.0% annually.

114 The main accelerator of the emissions embodied in services trade across the Global South is
115 the increasing trade of transportation. For example, Thailand increased the use of oil in inland
116 transport, especially after 2014, by 29.8% from 17.5Mt in 2014 to 22.7Mt in 2018. Therefore,
117 the emissions embodied in inland transport from Thailand to Indonesia increased sharply by
118 an average annual growth rate of 10.0% in 2014-2018, while the growth of inland transport
119 volume was only 0.6% (**Figure 1D**). Moreover, emissions drivers vary in the case of the trade
120 from developing to developed countries (from Vietnam to Japan) with respect to trade
121 between developing countries (from Thailand to Indonesia) and the difference would depend
122 on the modes of transportation in the countries involved. For example, Vietnam and Japan
123 mainly use air transport whereas Thailand and Indonesia mostly use inland waterway
124 transport.

125 However, in the case of North-South trade, business services and business travel
126 transportation are the main drivers of the growth in services trade volume and embodied
127 emissions. For example, in the services trade from the USA to China, air transportation has
128 increased rapidly at an annual growth rate of 8.7% during 2010-2018, especially high over
129 2010-2014 (18.0%). According to the Transportation Safety Administration report, the largest
130 U.S.-international country gateways for freight were in China in 2018. Total Freight from the
131 USA to China was up to 0.98 Mt for the year-ended December 2018. Therefore, the emissions
132 embodied in air transport have increased at the annual rate of 9.0% over 2010-2018.

133 **The determinants of the change in emissions**

134 Looking at the trend of emissions embodied in the global services trade during 2010-2018, it
135 appears that the biggest driver of rising emissions is the growing volume of trade, which
136 overall contributed 277.7 million tonnes (Mt) carbon emissions in 2018. This amount is
137 comparable to CO_2 emissions from the USA's annual services export in 2018 (282.6Mt).

138 The patterns of trade volume vary across different regions and different periods. Before 2016,
139 world trade grew at a low speed and consumption in major developed economies was
140 depressed. Therefore, exports of services from the global North were growing slowly (South-
141 North trade) and even decreased (North-North trade) during 2012-2016. For example, the
142 volume of services export from the USA to Japan decreased by 8.8 billion dollars during 2012-
143 2016, which contributed to the reduction of embodied emissions in services trade from the
144 USA to Japan by 6.3Mt. Moreover, during the same period, the volume of services exports
145 from Vietnam to Japan also decreased by 5.2% while emissions declined by only 0.09Mt. Due
146 to the relatively small impact of the international financial crisis on the developing economies,
147 both emerging and developing economies recovered rapidly and maintained strong trade
148 growth. During the years 2012-2016, the volume of South-South trade and North-South trade
149 increased to 50.7 billion dollars and 251.2 billion dollars, respectively. And the volume of
150 exports to the global South went up to 118.5Mt in 2016. For example, the USA exported more
151 services to China with the value of such exports going from 20.3 billion US dollars in 2012 to

152 23.1 in 2016, an increase of 14.0%. As a result, the emissions embodied in the services trade
153 increased by 3.0Mt. Similarly, the volume of trade in services going from Vietnam to China
154 and from India to China also increased, by 23.6% and 36.0% respectively, during 2012-2016,
155 with a corresponding increase in embodied emissions of 0.09Mt and 0.61Mt.

156 When consumption in developed countries recovered after 2016, trade volume became the
157 main driver of embodied emissions again (North-North trade and South-North trade) (**Figure
158 2A**). The trade volume from the USA to Japan increased to 10.3 billion dollars, which caused
159 an increase in embodied emissions by 0.66Mt over 2016-2018. At the same time, Vietnam
160 also increased services exports to Japan from 2.21 billion US dollars in 2016 to 2.47 in 2018.
161 The growth of the trade volume between Vietnam and Japan also contributed 87.6% (0.23Mt)
162 growth in embodied emissions. As for South-South trade, the growth rate of the volume of
163 services trade remains relatively lower than that of North-North and South-North patterns,
164 but the increasing trend has led to an increase in embodied emissions. During the years 2016-
165 2018, the volume of South-South services trade increased enormously and gave rise to
166 embodied emissions by almost 65.2Mt. (**Figure 2A**). For example, the increase of trade volume
167 from Thailand to Indonesia was up to 1.0 billion US dollars and contributed 0.82Mt of
168 embodied emissions over 2016-2018. Moreover, India increased the exports of services to
169 China at a rate of 26.5% and up to 7.68 billion US dollars in 2018, which resulted in a growth
170 of 0.50Mt emissions embodied in services trade. North-South trade also experienced a rapid
171 increase in trade in services from 2016 to 2018. After a slight decrease in trade volume, over
172 2016-2018 the USA increased exports of services to China from 23.1 billion US dollars in 2016
173 to 26.6 in 2018 and consequently, emissions embodied in services trade increased by 4.56 Mt.

174 Although still dominated by fossil fuels, from 2010 onwards the fuel energy mix saw the fastest
175 growth in the proportion of renewable sources[23]. Therefore, Figure 2A reflects the effect of
176 the transformation of the fuel mix on the supply chain of services trade[11] by showing that
177 emission intensity is the main decelerator of the global CO_2 emission reduction in 2010-2018,
178 However, in the global south, such as Vietnam and Thailand, emission intensity remains a
179 significant driver of the increase in emissions embodied in the services trade (South-South
180 trade, South-North trade). After 2014, the emission intensity of the supply chains of services
181 trade from Vietnam to Japan increased and contributed to growth of 0.31Mt in embodied
182 emissions over 2014-2016. Similarly, the emission intensity of services trade from Thailand to
183 Indonesia increased continuously and led to an increase of 0.90Mt in embodied emissions
184 during the years 2014-2018. Therefore, with developing countries playing a more important
185 role in international trade[8], we should pay more attention to the efforts and measures taken
186 by developing countries in terms of carbon emission intensity reduction in the international
187 services trade in the future.

188 **The pattern of services trade in the global south**

189 During 2010-2018, the annual growth rate of both services trade volume and emissions
190 embodied in services trade from the global South (5.5% and 2.0%) is larger than the global
191 North (4.4% and 1.0%). Especially, in South-North trade, the annual growth rate of embodied

emissions up to 3.3% during 2010-2018. Therefore, we pay more attention to the services trade of the global South, which increase largely **(Figure S1)**. Figure 3 shows that there are three main trade patterns of services trade in developing countries, whose annual growth rate is positive (**Table S4**). In Pattern 1, the global South has a closer bilateral trade relationship with the global North. For example, due to the poor infrastructure base, Ethiopia needs to import more transport equipment from developed countries **(Figure S2)**. During 2010-2018, Ethiopia imported an enormous amount of transport equipment from developed countries corresponding to an annual growth rate of 77.9% - the trade volume went from 8.75 million US dollars in 2010 to 878.5 million US dollars in 2018, especially with USA, Germany and France. In particular, Ethiopia imported 5.9 million US dollars of railways and tramways from France and 825.5 million US dollars of Aircraft from the USA in 2018. Because these kinds of equipment need to be fitted with corresponding ICT services at the same time, Ethiopia imported most ICT services, public and welfare services from developed countries, increasing by 31.3% and 25.0%, respectively. At the same time, more than 70% of the increase in air transport is due to exports to developed countries.

Similarly, in recent years Peru signed bilateral trade agreements with large economies including the USA, Canada, the European Union and Japan. The overall share of financial and business services Peru imported grew by an average annual growth rate of 8.4% over 2010-2018. Of this share, 98.9% is imported from developed countries. Moreover, Peru's tourism exports have been growing rapidly (8.8%), 54% of which are going to developed countries. In 2018, the share of foreign tourists coming from the USA went up to 15%.

In Pattern 2, developing countries import services mainly from other global South countries while establishing better trade cooperation with the global North. These countries (i.e. Philippines and Vietnam) export more to developed countries and import more services from developing countries. Tourism contributed 13% of the GDP of the Philippines. During the years 2010-2018, the export of tourism in the Philippines increased by 10.1% per year and the share of developed countries' visitors went up to 70%. Japan became the largest source of tourists to the Philippines over 2010-2018, with exports of tourism from the Philippines to Japan increasing from 1.2 billion US dollars in 2010 to 1.4 billion US dollars in 2018 by 12.7%. Moreover, given the strategic position, the Philippines are a potential gateway for investors to enter Southeast Asia and South Asia and therefore many multinational companies have their headquarters or representative offices in the Philippines. As a result, the imports of financial and business services in the Philippines increased largely by 19.5% per year over 2010-2018, 53% of which is imported from developing countries. For example, in 2018, China became the largest source of foreign investment in the Philippines. According to the official statistics of the Philippines, China's investment in the Philippines reached 50.69 billion Philippine pesos (about 975 million US dollars) in 2019, increasing by 20.72% from 2017.

In 2018, Vietnam's national shipping company saw a strong growth of volume of shipping, which is more than 13% and reach 24.3 million tons. More than 99% of Vietnam's water transportation was imported from developing countries. From 2010 to 2018, the growth rate of water transportation of Vietnam's imports went up to 25.7%. In addition, the health and medical services import in Vietnam increased by 17.4% per year during 2010-2018. Such trade

234	pattern has attracted many developing countries, especially China, to invest. In recent years,
235	Vietnam has invested in the healthcare and telemedicine services system, which has increased
236	exports of health services to other countries in the world. During the years 2010-2018,
237	Vietnam's exports of health services to Australia increased by 41.7% from 130 million US
238	dollars in 2010 to 184 million US dollars in 2018.

239	In Pattern 3, the focus is mostly on South-South cooperation. The countries in pattern 3 (i.e.
240	Mongolia and China) have stronger trade partnership with other global south countries. As
241	Mongolia is a land-locked country bordering China, the trade between Mongolia and China is
242	very close, which means that China has become the largest import and export country of
243	Mongolia. Although Mongolia's current imports from China are mainly grain agriculture and
244	machinery industry, Figure 3 shows that, in recent years, with the continuous improvement
245	of Mongolia's economy, Mongolia's demand for services, especially health services, is rising
246	rapidly. During the years 2010-2018, Mongolia's GDP has grown by 81.9%from 7.2 billion US
247	dollars in 2010 to 13.1 billion US dollars in 2018. And Mongolia's imports of public and welfare
248	services and health services grew at an average annual rate of 40.5% and 45.1%, respectively.

249	During the years 2010-2018, China's imports of tourism resources from other developing
250	countries grew by 12.3% per year. According to a report released by the World Tourism
251	Organization, the outbound tourism spending of Chinese tourists reached 277 billion US
252	dollars in 2018. At present, China is the world's largest exporter of tourists. Most tourists in
253	the Asian developing countries such as Thailand, Vietnam and Malaysia are Chinese. At the
254	same time, China and neighbouring developing countries have closer economic cooperation.
255	Over 2010-2018, China's exports of financial and business services increased by 7.7% per year,
256	with almost 81% of such exports going to developing countries.

257	## Discussion

258	Services trade is becoming increasingly important for global economic growth and its role is
259	likely to grow substantially over the next few years[24]. Services sectors, largely contributed by
260	the transportation, tourism and financial services, are more sensitive to the change in the
261	socioeconomic environment than merchandise trade. For example, the restriction of mobility
262	during the global pandemic will cause a huge drop in tourism and air transportation[25].
263	However, they are likely to rebound faster than other manufacturing industries once the
264	epidemic is under control[26]. The service industry is generally downstream of the supply chain,
265	which means the related carbon emissions embodied in services trade are contributed by the
266	upstream productions of supply chains. For the bilateral trade within global North, services
267	trade is mainly professional services (i.e. Renting and other business services) and requires
268	carbon emission reductions along the whole supply chain. Therefore, we need to advocate
269	financial institutions not only to reduce their own carbon emissions, but also push upstream
270	industries to green their production, such as using more renewable energy. Therefore, we
271	should design emission mitigation policies of services trade based on the whole supply chain.

272   In addition, the financial sector can advocate and formulate relevant low-carbon preferential
273   policies, such as increasing the convenience of lending to green industries and granting low-
274   interest loans to green and low-energy-consuming industries[27]. This can reduce the
275   production cost of the green industries and get better business performance, which can
276   promote the construction of a low-carbon supply chain[28,29].

277   It has been acknowledged that regional cooperation can help to accomplish global mitigation
278   objectives and it is easier for regions sharing common economic development structures,
279   common cultural backgrounds or even geographical proximity to decide on mitigation policies
280   or agreements[30-32]. Therefore, the global South countries tend to have closer bilateral
281   cooperation with each other, which needs to strengthen regional cooperation to achieve
282   collaborative emission reduction among South-South trade. There are some national policy-
283   oriented factors, such as China's "One Belt, One Road" policy, which is representative of
284   South-South cooperation. Services trade constructs a more close linkage between the "Belt
285   and Road" regions, and creates opportunities for cooperation and development[33,34].
286   Moreover, reducing the trade cost between the "Belt and Road" regions will help different
287   industries to further optimize the layout in the "Belt and Road" regions, quickly form a new
288   pattern of cross-border industrial division of labour and spatial agglomeration, which will
289   contribute to the emission mitigation of the "Belt and Road" regions. Moreover, the South
290   countries should not only strengthen the trade relationship with the Global North but also
291   introduce relevant low carbon technology, such as electrification and energy efficiency
292   improvement. At the same time, the North-South services trade should not only stop at the
293   merchandise trade and low-tech services trade (such as tourism), but also facilitate the
294   technical innovation and knowledge transfer services from global North countries , which can
295   help the capacity building of emerging countries and improve competitiveness of the global
296   South countries to participate in the global supply chain divisions. Therefore, a focus on
297   environmental initiatives at the regional cooperation is crucial.

298   Compared with merchandise trade, the intangible, non-storable, and contract-intensive
299   characteristics of services determine that services trade is more sensitive to differences in
300   systems, policies, laws and regulations among different trading countries[35-37]. The
301   characteristics of technology, knowledge and human capital intensiveness determine that
302   services trade is increasingly affected by information and communication technology[38].
303   Therefore, the application of information and communication technologies in developing
304   countries should be further strengthened to provide transnational service to the upstream
305   and downstream. As the bilateral trade between global North and global South are mainly
306   contributed by transportation and tourism. For example, the USA has growing business travel
307   by air to China, with a growth rate of 95.2% during the years 2010-2018. Therefore, the
308   policies and measures of changing trade pathways should be taken to reduce the emissions
309   embodied in North-South trade, such as, reducing the volume of business travel through more
310   online transactions. Moreover, it is worth noting that, during 2000-2017, trade costs in
311   services have declined at the rate of around 9%, which is about the same as in
312   manufacturing[39,40]. With the rapid development of digital technologies and online sales,
313   service sectors that have high trade costs (i.e. real estate activities, retail trade) witnessed a
314   precipitated decrease in trade costs. Therefore, countries will probably be able to both reduce

315 the embodied emissions and cut down trade costs in services trade by developing a digital
316 economy. At the same time, the digital economy shortens the supply chain, which makes the
317 supply chain more effective and reduces intermediate transactions[41,42].

318 There are some potential limitations in our results due to data availability. To reflect the latest
319 services trade pattern of developing economies, there are no MRIO databases available but
320 the one from Asian Development Bank (ADB[43], see details in the Method section), which can
321 provide the data of 2010-2018 time series. Therefore, despite the extensive spatial extent in
322 our study, especially the developing countries in Asia-Pacific region, we are not able to include
323 all developing regions in the world—for example, large parts of Africa and South America—
324 due to a lack of single country coverage of the MRIO database (ADB) we used.

Experimental Procedures

Resource availability

Lead contact

Further information requests should be directed to the Lead contact Jing Meng (jing.j.meng@ucl.ac.uk).

Materials availability

This study did not generate new unique materials.

Data and code availability

The time-series Multi-regional input-output tables (MRIOTs) are obtained from the Asian Development Bank (ADB) Multi-Regional Input-Output Tables Database. Because ADB MRIO table in 2018 has not been published publicly, the original MRIO data only is available from the corresponding leader in ADB database upon request. CO2 emissions from fuel combustion and energy consumption at the sectoral level in each region are from the IEA (International Energy Agency) database, which can be found by accessing the referenced studies. The Matlab code for reproducing the SDA analysis and source data for main figures presented in this study are available at Github: https://github.com/Jingwenhuo/Services_Trade.git.

Data sources

Time-series Multi-Regional Input-Output Tables (MRIOTs) are obtained from the Asian Development Bank (ADB) Multi-Regional Input-Output Tables Database[20]. The economic data from the ADB database are in current prices (US dollars). To remove the impact of inflation on the monetary output, we use the appropriate producer price index (PPI, National Accounts

346 Main Aggregates Database[43]) to adjust all of the monetary data to provide a consistent
347 analysis from 2010 to 2018.

348 CO_2 emissions from fuel combustion and energy consumption at the sectoral level in each
349 region are from the International Energy Agency (IEA) database[19]. Our analysis is global and
350 includes 19 service sectors (**Table S2**) and 59 regions.

351 Because ADB MRIOTs did not include Ethiopia and Peru (Figure 3), we obtained their services
352 trade data in 2018 from WTO[44] and their share data of trade with the global North from GTAP
353 10 MRIOT in 2014[45]. Other Asian developing countries services data and share data all come
354 from ADB MRIOT in 2018. The mapping between the WTO services data and GTAP MRIOT can
355 be found in **Table S3**.

356 **Scope of the services trade in this research**

357 According to the *Manual on Statistics of International Trade in Services 2010* (MSITS 2010),
358 services are defined as "heterogeneous outputs produced to order and typically consist of
359 changes in the condition of the consuming units realized by the activities of the producers at
360 the demand of the customers." The conventional statistical meaning of international trade in
361 services defines it as being between residents and non-residents of an economy, while the
362 MSITS 2010 extends the definition to include the value of services provided through foreign
363 affiliates established abroad. Based on these definitions, international trade in services are
364 divided into the following four models:
365
366 **Mode 1: Cross-border Supply**
367 from the territory of one economy into the territory of any other economy;
368 A user in country A receives services from abroad through its telecommunications or postal
369 infrastructure. Such supplies may include consultancy or market research reports, telemedical
370 advice, distance training, or architectural drawings.
371
372 **Mode 2: Consumption abroad**
373 in the territory of one economy the services are offered to a consumer of any other country;
374 The consumer consumes the services, such as tourist activities (tourists), learning courses
375 (students) or receiving medical treatment (patients) outside his/her home territory.
376
377 **Mode 3: Commercial presence**
378 by a service supplier of one economy, through commercial presence in the territory of any
379 other economy;
380 The service is provided within A by a locally-established affiliate, subsidiary, or representative
381 office of a foreign-owned and — controlled company (bank, hotel group, construction
382 company, etc.).
383 **Mode 4: Movement of natural persons**
384 by a service supplier of one economy, through the presence of natural persons of an economy
385 in the territory of any other economy;

386   A foreign national provides a service within A as an independent supplier (e.g., consultant,
387   health worker) or employee of a service supplier (e.g. consultancy firm, hospital, construction
388   company).
389

390   In this research, the international trade in services we studied mainly covers the first two
391   models of trade in services in the classification of GATS (General Agreement on Trade in
392   Services)[46]. The third model was excluded as it was not cross border activities. In addition,
393   services in some sectors - such as construction in the fourth model - were also not included in
394   this study because they were offered by non-service sectors.

395   **Emissions embodied in the services trade**

396   Environmental input-output analyses (EIOs)[35] have been widely used to evaluate the linkages
397   between economic activities and triggered environmental impacts. By environmentally
398   extending input–output (IO) analysis to multi-regional input-output (MRIO) analysis[47], the
399   emissions embodied in bilateral trade (EEBT) can be used to analyze bilateral interconnection
400   between industries in different regions due to trade-adjusted emission changes[48-50] and
401   assess attributions of environmental changes both from production and consumption[51].
402   Compared with MRIO, which only considers imports to final consumption and calculate
403   intermediate consumption endogenously, EEBT considers exports from each country covering
404   both intermediate and final products[1,52,53]. Therefore, EEBT is suitable to analyse the
405   interconnection of sectors in bilateral relationship[50]. Here, we estimate the emissions
406   embodied in services traded by using the global MRIO tables of 2010-2018. The monetary

407   balance of total outputs $\mathbf{x}^r$ of region r is:

408
$$\mathbf{x}^r = \mathbf{A}^r \mathbf{x}^r + \mathbf{y}^r + \mathbf{m}^{rs} - \mathbf{m}^{sr} \qquad (1)$$

409   where $\mathbf{x}^r$ is a sectoral output vector in region r; $\mathbf{A}^r$ represents the coefficients of

410   requirements in a region to produce per unit of output; $\mathbf{y}^r$ is the final demand (household,

411   government and investment) in region r. $\mathbf{m}^{rs}$ and $\mathbf{m}^{sr}$ are the bilateral exports and

412   imports from r to region s. In this study, we only consider the exports of service-sectors. EEBT

413   removes the imports required to produce the bilateral trade separating $\mathbf{x}^r$ into domestic

414   and traded parts to pay attention to domestic production[53]:

415
$$\mathbf{x}^r = \mathbf{A}^{rr} \mathbf{x}^r + \mathbf{y}^{rr} + \mathbf{m}^{rs} \qquad (2)$$

416   Where $\mathbf{A}^{rr}$ is the technical coefficient matrix of transactions within region r; $\mathbf{y}^{rr}$ is the

417   domestic final demand within region r.

418 In EEBT, the total CO_2 emissions produced in region r are as follows:

$$\mathbf{T}^r = \mathbf{F}^r \mathbf{x}^r = \mathbf{F}^r (\mathbf{I} - \mathbf{A}^{rr})^{-1}(\mathbf{y}^{rr} + \mathbf{m}^{rs})$$ (3)

420 where $\mathbf{F}^r$ is the direct emission vector to produce one unit output in region r [54]. As this study
421 focuses on the direct and indirect emissions related to the service industry along the supply
422 chain, emissions from all the sectors are considered, which means not zero here. In addition,

423 $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$ is the Leontief inverse matrix. $(\mathbf{I} - \mathbf{A}^{rr})^{-1}$ considers only the domestic supply

424 chain in region r. Again, the supply chains including all the industries are considered.
425 $\mathbf{T}^r$ can be decomposed into two components for the domestic demand $\mathbf{T}^{rr}$ (eq. (4)) and the
426 total emissions $\mathbf{T}^{rs}$ embodied in exports from region r to region s (eq. (5)):

$$\mathbf{T}^{rr} = \mathbf{F}^r (\mathbf{I} - \mathbf{A}^{rr})^{-1}\mathbf{y}^{rr} = \mathbf{F}^r \mathbf{L}^{rr}\mathbf{y}^{rr}$$ (4)

$$\mathbf{T}^{rs} = \mathbf{F}^r (\mathbf{I} - \mathbf{A}^{rr})^{-1}\mathbf{m}^{rs} = \mathbf{F}^r \mathbf{L}^{rr}\mathbf{m}^{rs}$$ (5)

429 **Structural Decomposition Analysis**

430 To analyze and quantify the driving factors behind the change of socio-economic indicators or
431 environmental economic system (i.e. energy consumption and CO_2 emissions), the two most
432 common decomposition methods used at the sectoral level are Index Decomposition Analysis
433 (IDAs) and Structural Decomposition Analysis (SDAs)[55]. Both IDA and SDA can decompose
434 these dependent variables into various independent determinants, with the main difference
435 between these two methods focusing on the model used. IDA uses only sectoral aggregation
436 data, while SDA uses the input-output framework[55]. Because the input-output model includes
437 indirect demand information captured by the Leontief inverse matrix, SDAs enable us to
438 distinguish a range of production effects and total final demand effects, such as structural,
439 production and socio-technical effects[23,54] and can assess both direct and indirect effects
440 where IDAs include direct effects only. In our analysis, we divided the change of embodied
441 emissions into four constituent parts: emission intensity, trade structure, production structure,
442 and trade volume effect[56].

443 The total CO_2 emissions embodied in producing the products exported from region r to region
444 s can be decomposed as follows:

$$
\begin{aligned}
\mathbf{T}^{rs} &= \mathbf{F}^r (\mathbf{I} - \mathbf{A}^{rr})^{-1}\mathbf{m}^{rs} \\
&= \sum_i \sum_j \sum_k \frac{c_i^r}{m_i^r} L_{ij}^{rr} m_j^{rs} \\
&= \sum_i \sum_j \sum_k \frac{c_i^r}{m_i^r} L_{ij}^{rr} \frac{m_j^{rs}}{m^{rs}} m^{rs} \\
&= \sum_i \sum_j \sum_k E_i^r L_{ij}^{rr} M_j^{rs} V^{rs}
\end{aligned}
$$ (6)

446 where c_i^{kr} is the emissions for total output in sector *i* in region *r*; m_i^r represents the total

447 output in sector *i* in region *r*; E_i^r indicates the emissions produced for a unit of output in

448 sector *i* in region *r*; L_{ij}^{rr} indicates the total inputs from sector *i* to produce one unit of output

449 in sector *j* in region *r*; M_j^{rs} is the share of the export of products in sector *j* from region *r* to

450 region *s* in the total exports from region *r* to region *s*; V^{rs} is the total export volume from

451 region *r* to region *s*.

452 Thus, the change in the emission transfers between two points in time (indicated by the

453 subscripts 0 and 1) can be expressed as $\Delta\mathbf{T}_a^{rs} = \mathbf{T}_1^{rs} - \mathbf{T}_0^{rs}$. However, a major problem of

454 structural decomposition techniques is that the decomposition is not unique. When the
455 number of factors is m, the number of all possible equivalent decompositions is equal to $m!$.
456 In order to resolve the non-uniqueness decomposition problem of SDAs, we apply an
457 established methods using the average of the termed polar decompositions as an
458 approximation of the average of all $m!$ equivalent decomposition forms[57]. The two polar

459 decompositions ($\Delta\mathbf{T}_a^{rs}$ and $\Delta\mathbf{T}_b^{rs}$) are as follows:

$$
\begin{aligned}
\Delta\mathbf{T}_a^{rs} &= \sum_i\sum_j\sum_k (\Delta E_i^r)\ L_{ij1}^{rr}M_{j1}^{rs}V_1^{rs} + \sum_i\sum_j\sum_k E_{i0}^r(\Delta L_{ij}^{rr})M_{j1}^{rs}V_1^{rs} \\
&+ \sum_i\sum_j\sum_k E_{i0}^r L_{ij0}^{rr}(\Delta M_j^{rs})V_1^{rs} + \sum_i\sum_j\sum_k E_{i0}^r L_{ij0}^{rr}M_{j0}^{rs}(\Delta V^{rs}) \\
&= \Delta\mathbf{E}_a + \Delta\mathbf{L}_a + \Delta\mathbf{M}_a + \Delta\mathbf{V}_a
\end{aligned}
\tag{7}
$$

$$
\begin{aligned}
\Delta\mathbf{T}_b^{rs} &= \sum_i\sum_j\sum_k (\Delta E_i^r)\ L_{ij0}^{rr}M_{j0}^{rs}V_0^{rs} + \sum_i\sum_j\sum_k E_{i1}^r(\Delta L_{ij}^{rr})M_{j0}^{rs}V_0^{rs} \\
&+ \sum_i\sum_j\sum_k E_{i1}^r L_{ij1}^{rr}(\Delta M_j^{rs})V_0^{rs} + \sum_i\sum_j\sum_k E_{i1}^r L_{ij1}^{rr}M_{j1}^{rs}(\Delta V^{rs}) \\
&= \Delta\mathbf{E}_b + \Delta\mathbf{L}_b + \Delta\mathbf{M}_b + \Delta\mathbf{V}_b
\end{aligned}
\tag{8}
$$

462 The average of the polar decomposition is expressed as follows:

$$
\begin{aligned}
\Delta\mathbf{T}^{rs} &= \frac{1}{2}[\Delta\mathbf{T}_a^{rs} + \Delta\mathbf{T}_b^{rs}] \\
&= \frac{1}{2}(\Delta\mathbf{E}_a + \Delta\mathbf{E}_b) + \frac{1}{2}(\Delta\mathbf{L}_a + \Delta\mathbf{L}_b) + \frac{1}{2}(\Delta\mathbf{M}_a + \Delta\mathbf{M}_b) + \frac{1}{2}(\Delta\mathbf{V}_a + \Delta\mathbf{V}_b) \\
&= \Delta\mathbf{E} + \Delta\mathbf{L} + \Delta\mathbf{M} + \Delta\mathbf{V}
\end{aligned}
\tag{9}
$$

464 where $\Delta \mathbf{T}^{\mathrm{rs}}$ is the growth in embodied emissions transfers between two points in time,
465 which in this study corresponds to 2010-2012, 2012-2014, 2014-2016 and 2016-2018. $\Delta \mathbf{E}$,
466 $\Delta \mathbf{L}$, $\Delta \mathbf{M}$ and $\Delta \mathbf{V}$ refer to the emission intensity effect, production structure effect,
467 trade structure effect and trade volume effect, respectively.

Acknowledgments

Author contributions

J.M. designed the study. J.H. and J. M. performed the analysis and prepared the manuscript.
J.H, J.M., Y.G., C.D. and J.X. interpreted the data. D.G. coordinated and supervised the project.
All authors participated in writing the manuscript.

Declaration of Interests

The authors declare no competing interests.

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638 **Figures titles and legends**
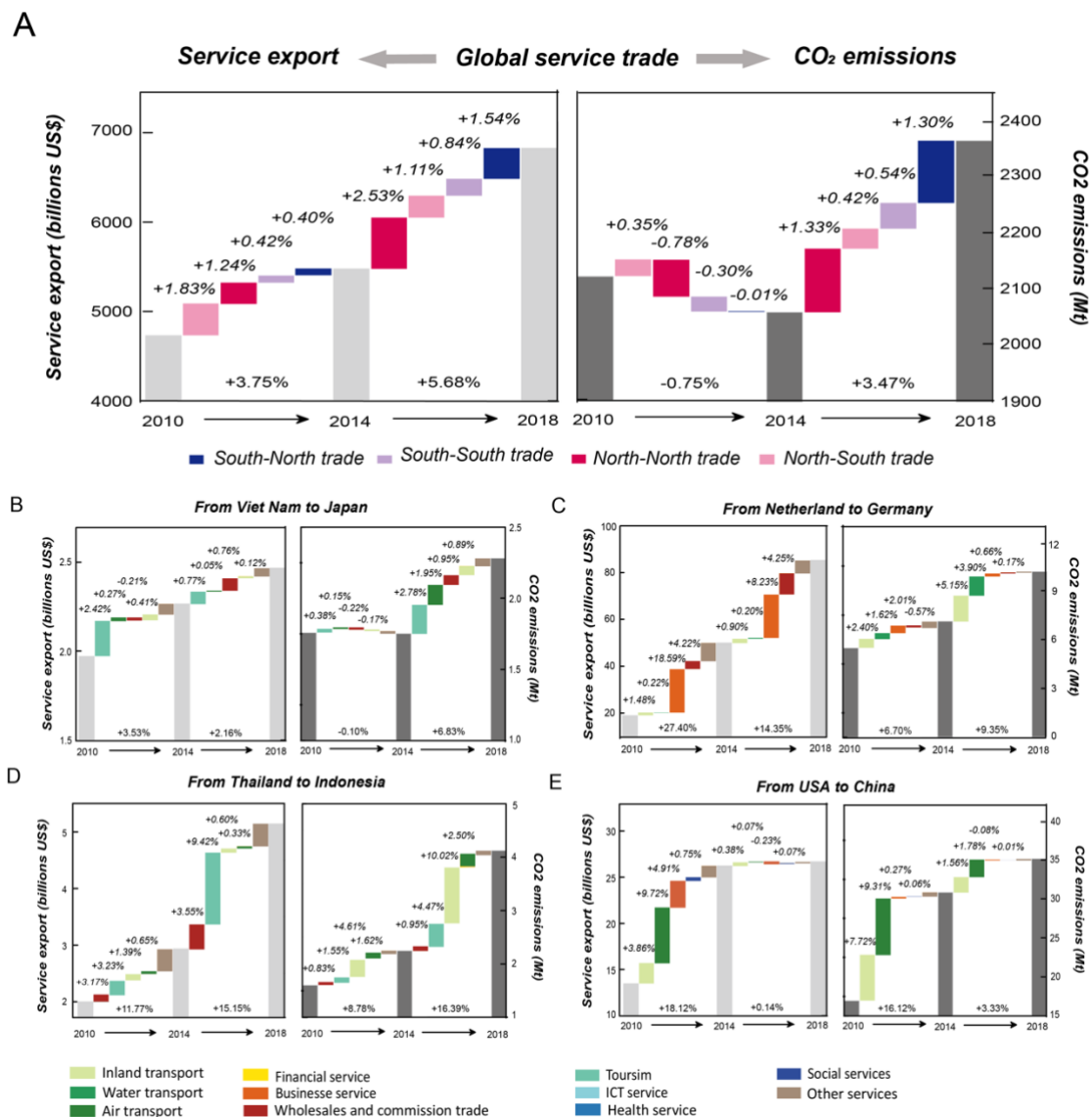

639

640   **Figure 1. The evolution of services trade pattern and the emissions embodied in services trade from**
641   **2010 to 2018.** Figure 1A presents the global services trade during 2010-2018. The left side (light grey
642   bars) represents the amount of services trade in billion dollars in constant price of 2010. The right side
643   (dark grey bars) represents the CO_2 emissions embodied in global services trade measured by million
644   tons. Blue bars are the trade flows from the global South to North, purple bars are from global South
645   to South; red bars are from the global North to North, pink bars are from global North to South. Figure

18

646 1B-E represents services trade (left side in billion US$) and emission flows (right side in Mt) for selected
647 countries. Color bars between grey bars represent sectoral contributions to increases of services trade.
648 The percentage figures are average annual growth rate during 2010-2018.
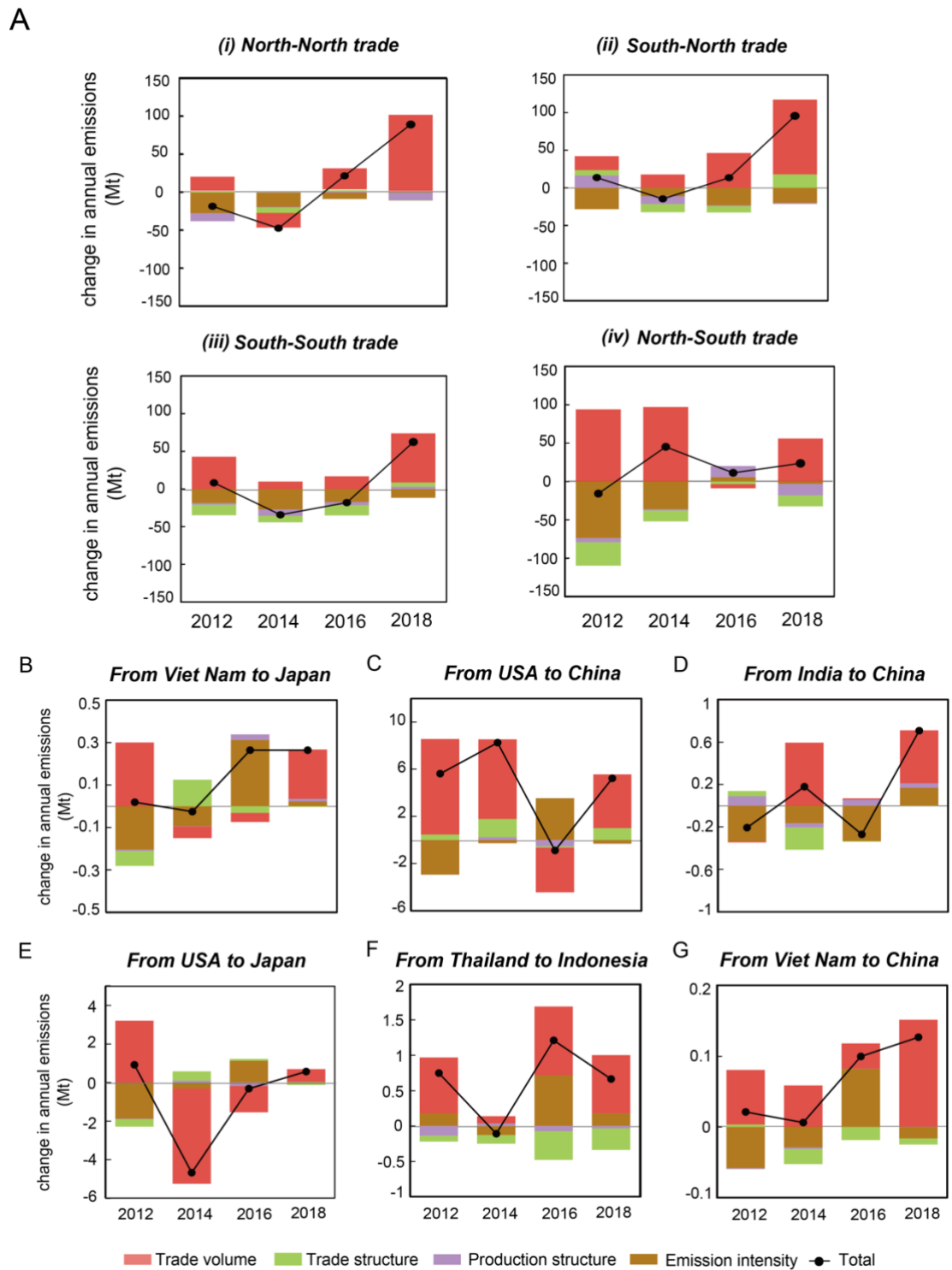
649

650 **Figure 2. Time-series structural decomposition of changes in emissions embodied in trade compared**
651 **to the previous year, over 2010-2018**. Figure 2A represents the decomposition results of changes in
652 emissions embodied in global services trade: (i) from developed regions (North) to developed regions
653 (North); (ii) from South to North; (iii) from South to South; (iv) and from North to South. Bars show the
654 contributions of four indicators: carbon intensity (CO_2 emissions/output), production structure, trade

19

structure, and trade volume. (See Method). Figure 2B-2G represents the decomposition of emissions change embodied in selected services flow between different countries.
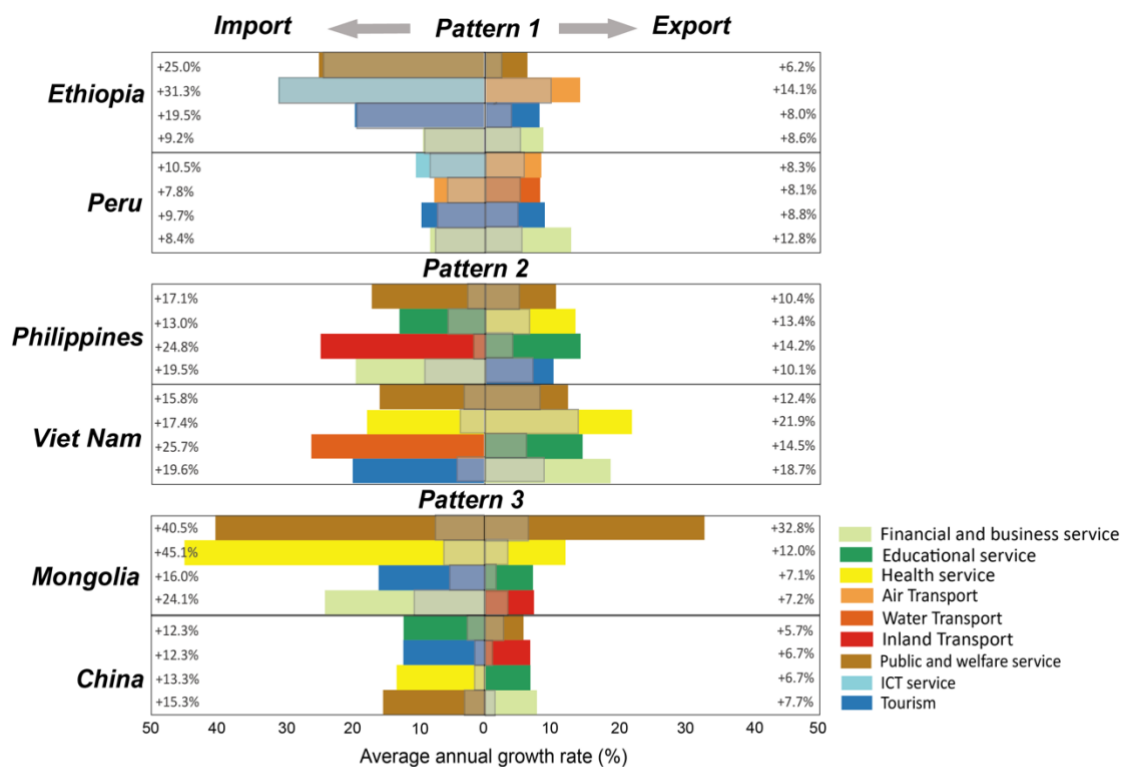
Figure 3. The composition of services export (on the right) and services import (on the left) in selected developing countries. Three modes of services trade across the global south are analyzed. Pattern 1: bilateral trade with the North; Pattern 2: mainly importing from the South whereas exporting to the North; Pattern 3: bilateral trade among countries of the global South. For countries in each pattern we showed the four services sectors with the largest average annual growth rate in imports and exports. Colors indicate the different services sectors with the largest average annual growth rate. The bars show the annual average contribution of each sector in 2010-2018. The gray shaded part of bars shows the share of the services trade volume these sectors trade with the global North.