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Embodied Carbon Dioxide Emission by the Globalized Economy: A Systems Ecological Input-Output Simulation

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ABSTRACT. This study presents an embodiment analysis of carbon dioxide (CO_2) emission originated in fossil fuels combustion for the world economy in 2004. A global embodied CO_2 intensity database associated with 112 regions and 57 sectors is obtained by applying the systems ecological input-output simulation, based on which the regional embodied CO_2 inventories are compiled to investigate the emissions instigated by particular economic activities. Globally, CO_2 emissions embodied in household fossil fuels combustion, in household commodity consumption, in government commodity consumption, and in investment are 3.99, 13.83, 2.07, and 5.22 Gt, respectively. As an indicator to reveal the average occupation of carbon welfare, regional per capita CO_2 emission embodied in consumption varies from 0.12 t in Ethiopia to 45.16 t in Rest of North America. The severe inequality between regions is characterized by the high Gini coefficients for CO_2 emissions (0.56 for direct emission and 0.58 for embodiment). And finally, the interregional carbon leakage in terms of net leakage, spill-over, and diversion is illustrated via dividing the world into three coalitions according to respective economic statuses.

Keywords: carbon dioxide, embodiment analysis, fossil energy, international trade, systems ecological input-output simulation, world economy

1. Introduction

The origins of embodiment analysis for resources and emissions can be traced back to the "embodied energy" studies (Costanza, 1980; Hannon, 1973; Odum, 1953; Odum, 1971) and its application attracts intensive concerns during recent years with development and acceptance of systems ecology theory (Brown and Ulgiati, 2004; Odum, 1996). Notably, the embodiment of greenhouse gas (GHG) emission (or more popularly, especially in the media, the carbon footprint, see Hammond, 2007) is of interest to not only scientists but also policy makers as well as the public owing to the global concerns on climate change issues (Hertwich and Peters, 2009; Lash and Wellington, 2007). Comparing to the direct emission account, the embodied analysis can be applied to identify GHG emission associated with particular purpose or economic activity (e.g., production, consumption, and trade) and thus provides substantial policy implication to allocate responsibility of anthropogenic emission (Peters, 2007).

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Given the broad intentions and significant meaning there is an emerging demand for embodied GHG studies, especially on the global level with international negotiations, cooperation, and conflicts on climate change issues appearing more and more frequently. Ahmad and Wyckoff (2003) estimated carbon dioxide (CO_2) emissions related to domestic consumptions of 24 countries for 1995 using national input-output tables extended by bilateral trade data, and Nakano et al. (2009) extended their results to 41 countries/regions for years around 1995 and 2000. Aggregating the world into 12 supra-national economies, Friot et al. (2007) and Wilting and Vringer (2009) separately processed multi-region environmental input-output modelling to analyze the global GHG emission on regional average. To investigate the embodiments of GHG and natural resources of the global economy as a whole, a single region simulation was carried out by Chen et al. (2009). With the international trading network taken into account, fruitful studies focusing on specific countries had also been presented for embodied GHG emission analyses (Ackerman et al., 2007; Li and Hewitt, 2008; Liu et al., 2010; McGregor et al., 2008; Nijdam et al., 2005; Peters et al., 2007; Weber and Matthews, 2007; Webber et al., 2008; Wiedmann et al., 2007; Xu et al., 2009). However, the "consis- tent comparative studies to understand our collective carbon footprint on a national or global level" are surprisingly very rare (Hertwich and Peters, 2009).

The aim of this study is to contribute to the "consistent comparative studies" via conducting a 112-region, 57-sector coupled systems ecological input-output simulation for CO_2 emission generated by fossil fuels combustion for the world economy in 2004, which is responsible for over half of the anthropogenic global warming effect according to the 100-year global warming potential (IPCC, 2007). In what follows, the CO_2 emission implies that "generated by fossil fuels combustion in 2004" if no extra denotation is provided. A global embodied CO_2 intensity database is calculated in the present study and the embodied emissions inventory for individual region is compiled accordingly to illustrate emissions instigated by different activities, i.e., household consumption, government consumption, investment, and interregional trades. The spatial distributions of carbon welfare along with equality issues are discussed and finally, the effects of carbon leakage are explored via dividing the world into three coalitions according to their respective economic statuses and capabilities to participate in mitigation action.

2. Materials and Methods

Both process chain analysis (e.g., life-cycle assessment) and network analysis (e.g., input-output method) were prevalently used in embodied account (Chen and Chen, 2010; Chen et al., 2010; Zhou, 2008), while their combination (Bullard et al., 1978) also attracted certain interests in recent years (Suh and Nakamura, 2007). Merits and drawbacks of each methodology had been discussed broadly (see e.g., Liang et al., 2007; Norman et al., 2007; Peters, 2007; Peters and Hertwich, 2006; Wiedmann, 2009; Wiedmann et al., 2007; Cai et al., 2009, 2010, 2011) and thus are not repeated here. For collective nation account, input-output method shows significant advantage to trace intricate chain of production process in time-efficient manner with low datum requirement (as necessary statistics are often well documented on national level). Therefore, a full-scale systems ecological input-output simulation considering the world as a closed economy is applied in the present study, where "full-scale" indicates all referred economies are endogenous and mutually dependent.

In the present model, each involved sector is accounted as an individual entry (the nominal "same" sectors from different economies are accounted as different entries). The core of the model is a multi-region economic input-output table complemented by concerned external ecological endowment flows, i.e., direct CO_2 emission for this study, as schematically shown in Table 1, in which n represents the total entry number, $t_{i,j}$ the monetary value of goods sold by Entry i to Entry j, d_i the monetary value of final demand of goods from Entry i, o_i the monetary value of total output of Entry i, f_i the volume of CO_2 released by Entry i directly, f_d the volume of CO_2 released by household directly, and f_o the volume of global CO_2 direct emission. For Entry i, the input-output balance in terms of embodied CO_2 flows can be formulated as:

$$f_i + \sum_j \varepsilon_i t_{j,I} = \varepsilon_i o_i, \quad (1)$$

$$o_i = \sum_j t_{i,j} + d_i, \quad (2)$$

where ε_i and ε_j denote the embodied CO_2 intensities of goods from Entries i and j, which imply the average amounts of direct plus indirect emissions released in the supply chains to produce one unit of goods by corresponding entries in current technology. Linking all balance formulae for the n entries a compressed matrix equation is obtained as:

$$F + ET = EP, \quad (3)$$

in which $F = [f_i]_{1\times n}$, $E = [\varepsilon_i]_{1\times n}$, $T = [t_{i,j}]_{n\times n}$, and $P = [p_{i,j}]_{n\times n}$ where $i, j \in (1,2\ldots n)$, $p_{i,j} = o_i$ $(i = j)$, and $p_{i,j} = 0$ $(i \neq j)$. With properly given direct CO_2 emission inventory (F), trade data between entries (T), and total sectoral output (P), the embodied CO_2 intensity can be obtained as:

$$E = F(P - T)^{-1}. \quad (4)$$

Introduce the direct CO_2 emission intensity $f = FP^{-1}$ and technology coefficients matrix $A = TP^{-1}$, along with the identity matrix I we have the famous Leontief Inverse Matrix expression of embodied intensity for closed economy as:

$$E = f(I - A)^{-1}. \quad (5)$$

And finally, the CO_2 emission embodied in any particular process can be calculated as:

$$X = EY + Z, \quad (6)$$

where Y is a vector showing commodity consumption and Z the direct emission for the concerned process.

Table 1. A Schematic Systems Ecological Input-Output Table Complemented by Direct CO_2 Emissions

From \ To		Entry purchase			Final demand	Total
		1	…	n		
Entry sale	1	$t_{1,1}$	…	$t_{1,n}$	d_1	o_1
	…	…		…	…	…
	n	$t_{n,1}$	…	$t_{n,n}$	d_n	o_n
Direct CO_2 emissions		f_1	…	f_n	f_d	f_o

Comparing to the direct emission, emission embodied in consumption (EEC) is a useful indicator to reveal the occupation of carbon welfare by residents, enterprises, and the government in a concerned region. Moreover, the emissions embodied in import (EEI) and export (EEE) are of special interest in defining the carbon trade balance: a region receives carbon surplus when its EEI exceeds EEE, and receives carbon deficit vice versa.

In the light of both the "strong" and "weak" definitions of carbon leakage (Peters and Hertwich, 2008; Peters, 2007), the essential impact of carbon shift associated with internatio-

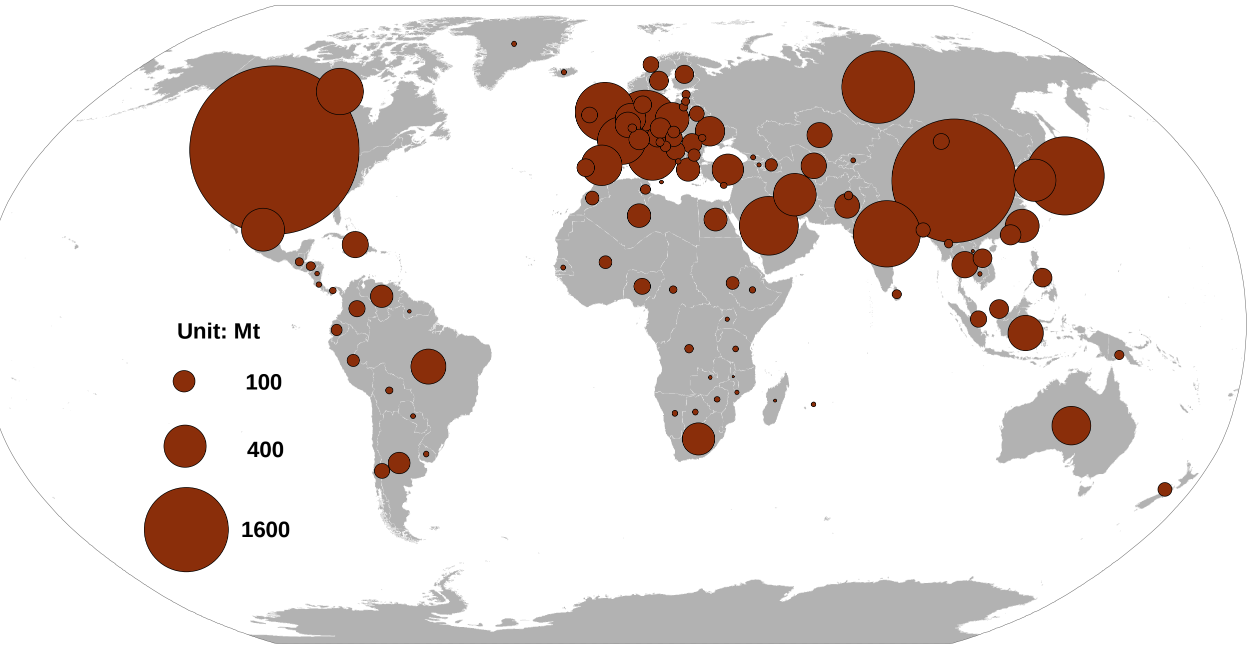

Figure 1. Spatial distribution of regional CO_2 EEC.

nal trade can be assessed by the integrate effect of total unchecked flows of GHG emissions, i.e., the synthesized consequence of EEI and EEE. Accordingly, the notion of "net leakage" is brought forward in this study to indicate the case that a developed economy gains carbon surplus from trade with developing economies, and "net spill-over" is defined vice versa. Besides, the "net diversion" effect is determined as the trade imbalance in terms of carbon embodiment between developed economies, which had not been paid sufficient attention in previous studies but is important for valid allocation of responsibility.

The Global Trade Analysis Project (GTAP) Database Version 7 Interim Release 2 is applied as the basis for our systems ecological input-output table, in which input-output tables as well as bilateral trade statistics for 57 sectors from 112 regions (93 nations/districts and 19 supra-national regions, see Appendix) are provided (Narayanan and Walmsley, 2008). The original intraregional input-output flows are adopted directly, while the trade data are disaggregated (Miller and Blair, 2009) to obtain the interregional import-export details. With all sectors and regions remaining disaggregated, the simulated network for this study has 6,384 × 6,384 trading flows. Regarding the fossil fuels statistics, the combustions of petroleum and gas products are estimated via subtracting feedstock from purchased volumes according to the GTAP energy dataset and documentation (Narayanan and Walmsley, 2008; Lee, 2008), while the non-energy use ratio of coal is estimated according to the national guideline of China (AQSIC/SAC, 2008), as it is the world's dominant coal producer as well as consumer. With the fossil fuels combustion data and the default emission factors (IPCC, 2006), direct CO_2 emissions by all entries and households are calculated according to the IPCC tier 1 method (IPCC, 2006). The final demand statistics and population of individual region for the analyzed year are also obtained from the GTAP dataset (Narayanan and Walmsley, 2008).

3. Results

3.1. Regional Embodiment

The embodied CO_2 intensity database for the 112 regions with detailed sectoral division is calculated based on which the global embodied CO_2 inventory is compiled and shown in Table 2. The results of this study are generally consistent with those from Hertwich and Peters (2009) and from Davis and Caldeira (2010), despite minor discrepancies occur due to differences in regions division, GHG categories inclusion, data source, or reference year. The global direct CO_2 emission, equal to the total embodiment in domestic final demand, amounts to 25.11 Gt, and the United States is the largest direct emitter on regional level followed by China (mainland), Russia, Japan, and India, which separately contributes to 23.10, 17.68, 6.00, 4.36, and 4.19% of that volume. As a result of the interregional trade, carbon surpluses are obtained by 67 nations/-districts and 13 supra-national regions when carbon deficits are obtained by the other 26 nations/districts and 6 supra-national regions, with the United States as the biggest CO_2 importer (1.34 Gt) and surplus receiver (0.59 Gt), in contrast to China (mainland) as biggest CO_2 exporter (1.47 Gt) and deficit receiver (0.99 Gt). Accordingly, the aforementioned regions separately accounts for 25.46, 13.72, 4.66, 5.48, and 3.95% of the global CO_2 emission in terms of EEC, as Japan exceeds Russia to take the third place. The total CO_2 emissions embodied in household fossil fuels consumption, in household commodity consumption, in government commodity consumption, and in investment account for 15.88, 55.09, 8.24, and 20.79% of the global EEC, summing up to 3.99, 13.83, 2.07, and 5.22 Gt, respectively.

Spatially, the regional CO_2 EEC concentrates in three areas

Table 2. Embodied CO_2 Inventory for the World in 2004

Region	FD (Mt)	HD (Mt)	EEI (Mt)	EEE (Mt)	EEC (Mt)	PCEEC (t)	HD (%)	HC (%)	GC (%)	Investment (%)
Albania	4.04	0.98	3.61	1.61	7.01	2.25	13.98	62.33	2.64	21.04
Argentina	100.10	27.99	21.55	44.22	105.42	2.75	26.55	50.48	5.20	17.77
Armenia	3.23	0.35	2.53	1.58	4.53	1.49	7.79	70.45	11.07	10.69
Australia	311.11	36.13	106.86	120.76	333.34	16.72	10.84	58.21	10.06	20.88
Austria	49.72	17.25	86.67	56.10	97.54	11.94	17.68	54.60	8.82	18.90
Azerbaijan	23.42	8.51	10.84	6.56	36.21	4.34	23.50	53.38	4.32	18.80
Bangladesh	26.88	6.47	21.77	8.44	46.68	0.34	13.85	63.89	2.10	20.16
Belarus	44.37	7.87	32.57	34.82	49.99	5.10	15.74	58.19	12.15	13.92
Belgium	73.22	28.41	192.57	144.06	150.15	14.41	18.92	53.36	9.57	18.14
Bolivia	9.18	2.29	2.30	2.86	10.91	1.21	21.04	60.43	9.66	8.87
Botswana	3.67	0.81	5.99	3.56	6.92	3.91	11.70	42.72	21.86	23.72
Brazil	236.81	59.55	79.69	103.32	272.74	1.48	21.84	55.11	6.45	16.60
Bulgaria	42.24	3.03	16.72	27.66	34.33	4.41	8.82	67.84	9.46	13.89
Cambodia	2.90	0.47	4.83	4.01	4.19	0.30	11.21	48.20	7.46	33.14
Canada	414.80	99.96	239.10	257.35	496.51	15.54	20.13	50.60	10.94	18.33
Chile	55.58	9.95	26.39	39.07	52.85	3.28	18.83	55.69	4.74	20.74
China (mainland)	4109.32	329.90	476.45	1469.60	3446.06	2.63	9.57	40.15	8.02	42.25
Colombia	44.57	12.41	17.63	14.64	59.97	1.33	20.69	55.58	6.33	17.40
Costa Rica	3.91	1.59	7.32	5.29	7.53	1.77	21.10	58.50	3.33	17.06
Croatia	15.55	4.40	14.67	10.28	24.33	5.36	18.08	54.73	10.17	17.03
Cyprus	6.69	0.93	7.31	5.03	9.90	11.99	9.41	61.84	8.24	20.51
Czech Republic	96.70	13.57	48.49	63.70	95.06	9.29	14.28	53.72	16.80	15.21
Denmark	44.32	8.87	59.29	40.68	71.81	13.27	12.36	55.77	13.14	18.73
Ecuador	16.27	6.07	9.66	5.02	26.97	2.07	22.50	59.53	3.57	14.40
Egypt	110.70	23.24	23.21	40.45	116.70	1.61	19.92	58.35	8.51	13.22
Estonia	15.03	1.10	9.48	10.96	14.66	10.94	7.54	67.25	10.84	14.37
Ethiopia	3.48	2.06	5.56	2.29	8.81	0.12	23.37	50.91	8.41	17.30
Finland	57.35	7.46	57.96	46.65	76.12	14.53	9.80	59.17	12.51	18.51
France	250.87	115.36	330.71	180.10	516.85	8.58	22.32	55.90	8.11	13.66
Georgia	2.30	1.32	3.97	1.52	6.08	1.34	21.73	56.70	3.60	17.97
Germany	585.65	184.82	595.92	394.52	971.87	11.76	19.02	55.49	9.60	15.89
Greece	78.03	17.12	69.43	41.60	122.98	11.08	13.92	64.47	5.67	15.94
Guatemala	8.03	2.74	8.29	3.73	15.32	1.25	17.87	59.86	1.48	20.80
Hong Kong, China	52.74	2.81	109.10	69.93	94.72	13.61	2.96	67.24	6.62	23.17
Hungary	40.25	14.32	45.39	35.11	64.84	6.41	22.09	54.79	8.59	14.53
India	917.73	134.54	141.30	200.64	992.93	0.91	13.55	57.78	5.27	23.40
Indonesia	251.81	58.16	73.30	100.93	282.35	1.28	20.60	53.92	5.87	19.62
Iran	268.21	128.98	58.50	48.23	407.46	5.92	31.66	39.62	5.11	23.62
Ireland	33.77	10.99	55.86	45.06	55.56	13.62	19.78	50.83	8.02	21.38
Italy	326.59	102.26	306.27	174.61	560.51	9.66	18.24	57.33	7.38	17.05
Japan	933.98	160.43	557.11	274.42	1377.09	10.77	11.65	53.70	10.70	23.95
Kazakhstan	164.41	4.22	30.33	58.67	140.29	9.45	3.01	62.45	17.82	16.72
Korea	342.66	53.72	256.54	253.95	398.97	8.37	13.46	50.94	7.27	28.33
Kyrgyztan	4.85	0.57	3.54	2.78	6.18	1.19	9.18	66.51	12.90	11.41
Laos	1.44	0.28	1.25	0.70	2.27	0.39	12.40	48.59	14.04	24.97
Latvia	6.68	1.42	11.25	5.79	13.56	5.85	10.50	57.77	11.36	20.38
Lithuania	11.70	1.62	14.63	11.60	16.36	4.76	9.93	59.83	9.10	21.14
Luxembourg	9.16	3.96	20.30	18.50	14.93	32.95	26.56	45.59	7.46	20.39
Madagascar	1.28	0.39	1.80	1.11	2.35	0.13	16.36	65.57	3.47	14.60
Malawi	0.52	0.17	1.51	0.51	1.69	0.13	10.00	67.37	11.55	11.08
Malaysia	102.24	18.53	93.38	135.62	78.53	3.16	23.60	48.17	9.07	19.17
Malta	2.57	0.28	3.01	2.48	3.38	8.43	8.21	67.97	11.06	12.76
Mauritius	1.73	0.55	4.90	2.71	4.48	3.64	12.37	54.62	6.60	26.40

Table 2. (continued.)

Region	FD (Mt)	HD (Mt)	EEI (Mt)	EEE (Mt)	EEC (Mt)	PCEEC (t)	HD (%)	HC (%)	GC (%)	Investment (%)
Mauritius	1.73	0.55	4.90	2.71	4.48	3.64	12.37	54.62	6.60	26.40
Mexico	297.09	75.54	143.69	111.90	404.42	3.83	18.68	58.75	3.43	19.15
Morocco	30.90	4.93	19.06	12.36	42.53	1.37	11.58	49.45	19.97	19.00
Mozambique	1.51	0.51	3.68	1.65	4.06	0.21	12.64	56.19	8.64	22.54
Netherlands	170.77	34.22	162.59	161.79	205.79	12.68	16.63	56.60	11.09	15.68
New Zealand	32.23	5.91	22.68	19.19	41.62	10.43	14.19	55.53	8.01	22.27
Nicaragua	3.40	0.60	2.39	1.52	4.87	0.91	12.40	62.15	5.82	19.63
Nigeria	36.82	14.76	22.58	16.51	57.66	0.45	25.60	38.78	13.09	22.54
Norway	32.30	5.00	56.87	38.85	55.32	12.03	9.03	55.35	11.14	24.48
Pakistan	105.87	19.57	36.55	20.36	141.64	0.92	13.82	63.25	3.40	19.53
Panama	4.59	1.09	7.67	3.95	9.41	2.96	11.62	71.55	6.72	10.12
Paraguay	2.70	1.18	3.11	1.62	5.37	0.89	21.98	64.15	1.45	12.42
Peru	24.90	5.39	10.71	6.21	34.79	1.26	15.49	67.93	4.18	12.39
Philippines	63.94	10.75	42.43	36.64	80.48	0.99	13.36	66.02	5.42	15.20
Poland	245.72	38.08	64.44	92.86	255.39	6.62	14.91	68.63	6.76	9.70
Portugal	48.83	9.44	40.57	27.37	71.48	6.85	13.21	59.44	9.04	18.31
Rest of Caribbean	139.98	22.03	49.63	53.81	157.83	4.10	13.96	65.41	3.09	17.54
Romania	76.69	12.60	29.42	34.65	84.06	3.86	14.99	62.29	8.47	14.25
Russia	1304.67	202.21	138.37	474.42	1170.82	8.14	17.27	60.91	9.12	12.70
Senegal	3.93	0.88	3.11	1.54	6.39	0.56	13.81	66.87	5.35	13.97
Singapore	35.66	2.47	135.20	112.87	60.45	14.16	4.09	56.47	10.96	28.48
Slovakia	26.18	5.27	24.93	25.11	31.28	5.79	16.86	56.84	10.22	16.07
Slovenia	12.18	3.36	13.57	12.39	16.71	8.48	20.09	51.17	10.16	18.59
South Africa	321.42	29.60	46.35	165.47	231.91	4.91	12.76	64.73	7.59	14.92
Spain	260.42	51.99	186.03	130.76	367.67	8.62	14.14	50.34	8.87	26.66
Sri Lanka	10.37	2.31	12.54	7.10	18.11	0.88	12.73	62.47	5.09	19.71
Sweden	37.76	10.80	78.08	45.95	80.70	8.96	13.38	53.27	17.57	15.77
Switzerland	25.76	18.78	96.06	50.57	90.04	12.44	20.86	48.31	4.68	26.15
Taiwan, China	221.67	21.19	160.51	219.04	184.32	8.10	11.49	62.07	6.12	20.32
Tanzania	2.86	1.30	5.26	1.62	7.80	0.21	16.65	56.33	5.68	21.34
Thailand	172.56	22.82	99.68	138.11	156.95	2.46	14.54	52.62	6.96	25.87
Tunisia	17.37	3.64	12.60	11.46	22.15	2.22	16.43	58.17	7.77	17.62
Turkey	162.81	37.00	99.95	77.68	222.09	3.08	16.66	59.10	3.93	20.32
Uganda	2.14	0.67	2.13	0.95	3.99	0.14	16.84	45.85	14.09	23.21
Ukraine	237.31	53.65	54.87	154.03	191.80	4.08	27.97	53.22	7.71	11.10
United Kingdom	421.68	143.82	414.36	192.51	787.35	13.24	18.27	56.03	10.29	15.42
United States	4696.49	1105.05	1343.81	751.03	6394.33	21.65	17.28	60.95	7.29	14.48
Uruguay	4.16	1.13	5.13	3.02	7.40	2.15	15.24	62.05	8.86	13.84
Venezuela	119.80	24.75	15.96	49.10	111.40	4.24	22.22	49.96	8.51	19.31
Viet Nam	66.90	12.83	49.54	48.64	80.63	0.97	15.92	47.64	3.67	32.77
Zambia	1.71	0.37	3.12	1.73	3.48	0.30	10.76	55.52	9.53	24.19
Zimbabwe	9.20	0.61	3.91	5.83	7.88	0.61	7.72	70.01	9.86	12.41
Rest of Central Africa	7.36	2.86	6.95	2.86	14.31	0.40	20.01	47.00	7.03	25.96
Rest of Central America	10.37	2.74	11.09	6.04	18.16	1.29	15.08	66.10	4.14	14.68
Rest of East Asia	69.33	1.76	12.42	26.19	57.32	2.26	3.07	35.02	21.97	39.93
Rest of Eastern Africa	19.88	4.87	22.22	7.43	39.54	0.40	12.33	58.19	9.69	19.80
Rest of Eastern Europe	5.64	1.97	6.54	3.73	10.42	2.47	18.87	53.97	12.41	14.75
Rest of Europe	70.90	7.41	20.52	23.78	75.06	5.25	9.87	66.81	6.62	16.70
Rest of European FTA	4.52	0.73	5.41	4.38	6.29	19.40	11.66	60.72	7.95	19.68
Rest of Former SU	131.37	52.78	15.54	53.27	146.42	3.91	36.05	39.12	14.19	10.64
Rest of North Africa	85.72	31.47	29.89	24.27	122.81	3.22	25.63	51.80	2.50	20.08
Rest of North America	2.97	0.65	2.97	0.81	5.78	45.16	11.20	61.31	11.40	16.09
Rest of Oceania	16.63	2.21	8.78	8.29	19.32	2.22	11.41	54.24	14.40	19.95

Table 2. (continued.)

Region	FD (Mt)	HD (Mt)	EEI (Mt)	EEE (Mt)	EEC (Mt)	PCEEC (t)	HD (%)	HC (%)	GC (%)	Investment (%)
Rest of South African Customs	3.24	1.01	8.23	5.56	6.93	1.43	14.53	49.38	9.11	26.97
Rest of South America	1.75	0.39	1.86	1.29	2.71	1.95	14.39	60.57	11.77	13.27
Rest of South Asia	7.88	2.06	9.54	2.89	16.59	0.29	12.42	57.07	9.48	21.03
Rest of South Central Africa	8.45	2.08	9.16	4.01	15.68	0.22	13.30	42.90	23.06	20.74
Rest of Southeast Asia	14.53	2.27	6.04	7.38	15.46	0.30	14.66	57.12	8.03	20.20
Rest of Western Africa	18.62	6.16	24.77	10.13	39.42	0.34	15.63	61.06	5.61	17.69
Rest of Western Asia	827.95	103.65	243.48	407.32	767.77	6.48	13.50	57.84	14.34	14.32
World	21124.74	3986.40	8557.18	8557.18	25111.13	3.92	15.88	55.09	8.24	20.79

*FD: Firm direct; HD: Household direct; PCEEC: Per capita EEC; HC: Household commodity; GC: Government commodity; HD, HC, GC and Investment are share of (per capita) EEC.

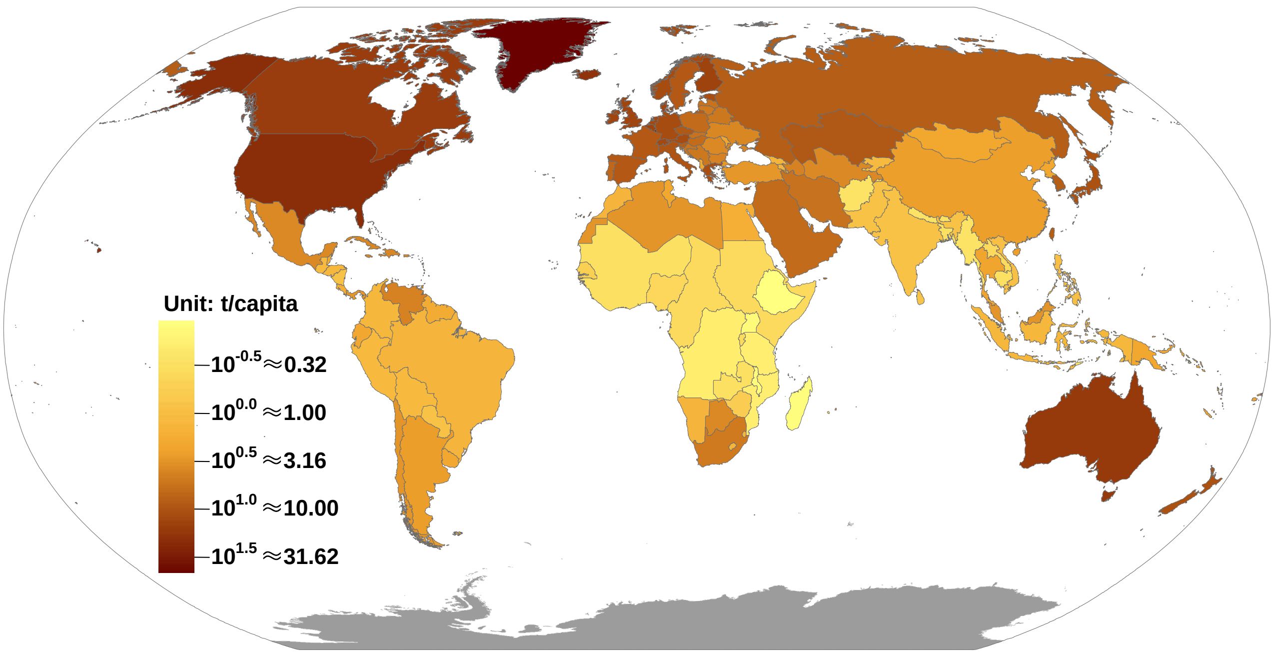

Figure 2. Spatial distribution of regional per capita CO_2 EEC.

as North American carbon sphere centered on the United States, European carbon sphere centered on the Western Europe, and Far East plus India carbon sphere centered on China (see Figure 1). Comparing to other final demand categories, investment often attracts special attention because considerable portion of investment is used for production (Chen et al., 2010; Peters and Hertwich, 2008; Zhou, 2008). It is interesting to find that several regions in Asia, especially those covered in the "East Asia Culture Sphere" (China, Japan, Korea, Singapore, Vietnam, etc.), have high ratio of CO_2 emissions embodied in investment (normalized by regional EEC), which implies significant influence of cultural factors. Besides, some of the African economies have relatively high investment ratios due to their poor existing infrastructure conditions.

3.2. Per Capita Carbon Welfare

Equality is an important topic for international climate negotiation. Global distribution of carbon welfare in terms of per capita EEC is extremely unbalanced and the general trend is that resident in richer region shares higher welfare (see Figure 2). Average per capita CO_2 EECs for the accounted nations/-districts vary from less than 0.30 t in six African countries to over 20 t in Luxembourg and the United States, while the gap is even larger on supra-national level as from 0.22 t in Rest of South Central Africa to 45.16 t in Rest of North America (see Table 2). Meanwhile, a rotated V-shape distribution of per capita carbon welfare around the equator is observed, most explicitly in the Asia Pacific area, in the Latin American area, and in the African continent. This geographic distribution along latitude suggests that climate factor also has considerable impact on fossil energy consumption, especially for less developed areas.

The inequality of carbon welfare are portrayed in Figure 3, in which the continuous piecewise linear Lorenz Curves are applied to indicate the dispersions of CO_2 direct emission and EEC as well as monetary expenditure between regions. The Gini coefficients of direct and embodied emissions for the entire world are calculated to be 0.56 and 0.58, both of which are lower than that of monetary expenditure (0.74) but still imply severe inequality between regions. Moreover, the larger Gini coefficient for embodiment also suggests that conventional direct emission account underestimates the inequality of carbon welfare.

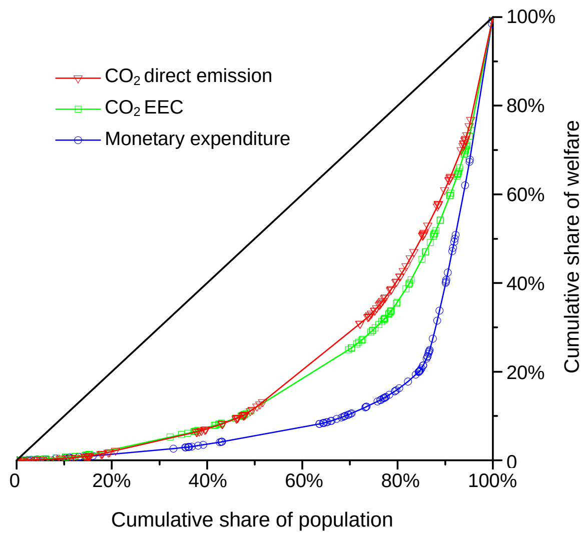

Figure 3. Lorenz Curves indicating dispersion of welfare in terms of CO_2 direct emission, CO_2 EEC, and monetary.

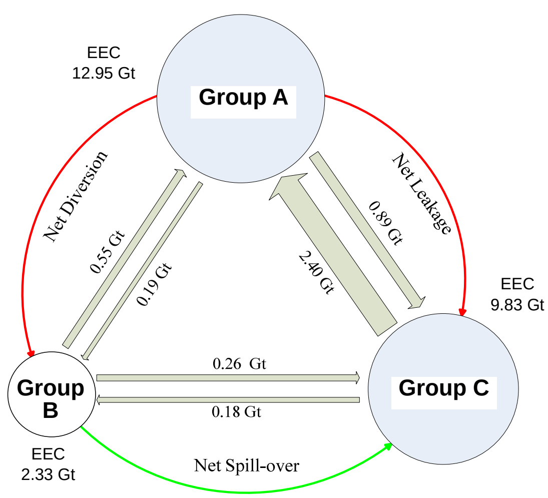

Figure 4. Multilateral trade balance in terms of CO_2 embodiment.

3.3. Carbon Leakage between Coalitions

International coalition is a promising and effective strategy to achieve the global abatement goal (Peters and Hertwich, 2008). On the basis of the "common but differentiated responsibility and respective capability" principle and referring to the regional division of this study, the accounted 112 regions are aggregated into three groups: Group A as the most developed economy including 23 regions which is able to take major action for GHG mitigation; Group B as the transitional economy covering 17 regions which has limited capability in current stage; and Group C as the rest of the world composed mostly of developing economies whose first priority is to escape from poverty and enhance domestic welfare and thus are only able to participate when developed countries supply enough funding and technology (detailed grouping is presented in Table 3). With 13.66% of global population, Group A accounts for 44.11% of global direct CO_2 emissions and 51.55% of global EEC. Similar direct emissions (44.82% of global) along with remarkably less EEC (39.15% of global) is shared by 79.91% of the global populations from Group C, while the corresponding fractions for Group B as a transition are 11.07%, 9.30%, and 6.43%. These results imply supplemental evident for the unequal distribution of carbon welfare and confirm the necessity to allocate mitigation responsibility discriminatingly. The multilateral trade balance for the three groups is depicted in Figure 4, according to which the substantial effects impacting the effectiveness of current abatement policy are observed as: (a) net leakage from Group A to Group C which makes due responsibility (1.50 Gt, or 5.99% of global emission) of the former group unchecked; (b) net spill-over from Group B to Group C which makes essential effort (0.08 Gt, or 0.32% of global emission) of the former group unrecognized; and (c) net diversion from Group A to Group B which shifts emission (0.36 Gt, or 1.45% of global emission) from the former to the latter group and undermines the valid evaluations of domestic responsibilities according to direct emission.

4. Conclusions

The effectiveness and fairness of existing GHG abatement policy applied in the Kyoto Protocol system based on producer responsibility principle is questionable as carbon surplus receivers avoid part of their due burdens while carbon deficit receivers are assigned excessive obligations. In view of the necessity to allocate responsibility associated with particular economic activity, this study analyzes the embodiment of CO_2 emissions generated by fossil fuels combustion for the world in 2004 on a collective nation (region) level using a full-scale systems ecological input-output simulation with implications for general GHG mitigation policy.

With the interregional trading flows taken into account, the traditional direct emission statistics are adjusted to obtain the embodied emission inventories for 112 regions covering the world. For the global economy as a whole, over 70% of the CO_2 emission is embodied in household consumption, with a little more than 20% in investment and less than 10% in government consumption. Owing to the diverse economic structure as well as technology level, the distribution of regional carbon balance is polarized: most developed economies receive carbon surplus via importing carbon-intensive products and exporting high value-added but less carbon-intensive ones (except some resource-abundant regions which export considerable natural resources, e.g., Australia, Canada, and Russia), and many of the least developed economies, especially those in the Africa, also receive carbon surplus because they have to sell preliminary products with low carbon intensity to exchange manufactured ones with higher intensity in the international market.

Regarding the equality issue which had been extensively discussed, regional carbon welfare in terms of per capita CO_2

Table 3. Mapping from the 112 Regions to the 3 Coalitions

Region	Coalitions	Region	Coalitions
Albania	Group C	Netherlands	Group A
Argentina	Group C	New Zealand	Group A
Armenia	Group C	Nicaragua	Group C
Australia	Group A	Nigeria	Group C
Austria	Group A	Norway	Group A
Azerbaijan	Group C	Pakistan	Group C
Bangladesh	Group C	Panama	Group C
Belarus	Group B	Paraguay	Group C
Belgium	Group A	Peru	Group C
Bolivia	Group C	Philippines	Group C
Botswana	Group C	Poland	Group B
Brazil	Group C	Portugal	Group A
Bulgaria	Group B	Rest of Caribbean	Group B
Cambodia	Group C	Romania	Group B
Canada	Group A	Russia	Group C
Chile	Group C	Senegal	Group C
China (mainland)	Group C	Singapore	Group B
Colombia	Group C	Slovakia	Group B
Costa Rica	Group C	Slovenia	Group C
Croatia	Group B	South Africa	Group A
Cyprus	Group C	Spain	Group C
Czech Republic	Group B	Sri Lanka	Group A
Denmark	Group A	Sweden	Group A
Ecuador	Group C	Switzerland	Group C
Egypt	Group C	Taiwan, China	Group C
Estonia	Group B	Tanzania	Group C
Ethiopia	Group C	Thailand	Group C
Finland	Group A	Tunisia	Group B
France	Group A	Turkey	Group C
Georgia	Group C	Uganda	Group B
Germany	Group A	Ukraine	Group A
Greece	Group A	United Kingdom	Group A
Guatemala	Group C	United States	Group C
Hong Kong, China	Group C	Uruguay	Group C
Hungary	Group B	Venezuela	Group C
India	Group C	Viet Nam	Group C
Indonesia	Group C	Zambia	Group C
Iran	Group C	Zimbabwe	Group C
Ireland	Group A	Rest of Central Africa	Group C
Italy	Group A	Rest of Central America	Group C
Japan	Group A	Rest of East Asia	Group C
Kazakhstan	Group C	Rest of Eastern Africa	Group C
Korea	Group C	Rest of Eastern Europe	Group C
Kyrgyztan	Group C	Rest of Europe	Group C
Laos	Group C	Rest of European Free Trade Association	Group B
Latvia	Group B	Rest of Former Soviet Union	Group C
Lithuania	Group B	Rest of North Africa	Group C
Luxembourg	Group A	Rest of North America	Group A
Madagascar	Group C	Rest of Oceania	Group C
Malawi	Group C	Rest of South African Customs	Group C
Malaysia	Group C	Rest of South America	Group C
Malta	Group C	Rest of South Asia	Group C
Mauritius	Group C	Rest of South Central Africa	Group C
Mexico	Group C	Rest of Southeast Asia	Group C
Morocco	Group B	Rest of Western Africa	Group C
Mozambique	Group C	Rest of Western Asia	Group C

EEC is calculated and the result ranges from 0.12 t in Ethiopia to 45.16 t in Rest of North America. Besides, this research does the first time to apply the Gini coefficient to indicate the dispersion of carbon welfare in terms of both CO_2 direct emission and embodiment, based on which the sever inequality between regions is confirmed. Moreover, comparing to that for monetary expenditure, the higher Lorenz Curves for carbon welfare imply an approximate trend that poorer economy has higher elasticity of CO_2 emission with expenditure than richer economy, which gives rise to the necessity to reserve more emission room for the poorer one for future development. Results also suggest that traditional account based on direct emission underestimates the inequality of carbon welfare distribution. For the entire world, it should be noticed that the Gini coefficient for regions is smaller than that for individual, thus the distribution of carbon welfare between individuals is essentially more diverse than that between regions which is assessed in this study.

The issue of carbon leakage introduced by separation of production and consumption had been discussed extensively owing to its potential to undermine the effectiveness of current mitigation policy (IPCC, 2007; Pan et al., 2008). Referring to the newly advanced indicators synthesizing EEI and EEE, this study explores the impact of unchecked carbon emissions via aggregating the 112 regions into three groups according to their respective economic statuses and capacities to participate in mitigation action. Results show that the most developed economy avoids its responsibility via not only importing carbon-intensive goods from the developing economy but also shifting carbon emission to the economy in transition. Despite the existence of net spill-over benefits global CO_2 regulation through bringing extra participation (imported final demand of developing economy is constrained), this effect also impacts the positiveness of deficit receiver and thus should be seriously taken into account in climate negotiation.

As a collective study, this paper presents an embodiment analysis to evaluate the CO_2 emissions instigated by economic activities such as consumption, investment, and trade to reveal the occupation of carbon welfare on regional level. Based on this outlook of the world, future exploration with more particular concern on a single region or a specific industry can be carried out using the provided preliminary database. Moreover, the economic structure of the world as well as any concerned region should be investigated in detail to provide concrete policy advisement for economy adjustment to approach a low-carbon future.

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