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Analysis

How does consumer behavior influence regional ecological footprints? An empirical analysis for Chinese regions based on the multi-region input–output model

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ABSTRACT

The calculation of national ecological footprints using world average productivities can lead to biased results due to the neglect of spatial variation in in-situ ecological impacts. To address this issue, we apply a regional approach to generate ecological footprints based on the multi-region input–output model. This method enables us to trace the origin of regional consumption and to systematically account for the ecological impacts embodied in interregional trade. By using decomposition analysis, we attribute regional differences in ecological footprints to three behavioral factors associated with consumption: the selection of production origins, the structure of consumption and the level of expenditure. An empirical study for China's eight regions shows substantial cross-regional variation in terms of the amount of land appropriation and the mix of land types. The empirical study also confirms that not only how much is being consumed and what is being consumed, but also geographical origins (and, by implication, regionally specific production processes and methods) influence consumption-induced ecological impacts. This paper therefore sheds light on the importance of accounting for interregional variation in consumer behaviors and recommends customized solutions to achieve effective reductions in regional ecological footprints.

1. Introduction

Defined as "the total area of productive land and water area required continuously to produce all the resources consumed and to assimilate all the wastes produced, by a defined population, wherever on earth that land is located" (Rees and Wackernagel, 1996), ecological footprint (EF) is used as a proxy to measure various ecological impacts of human activities and consumption. By comparing the balance between land appropriation and bio-capacity, EF has become an indicator of ecological sustainability, drawing the attention of policymakers and raising the awareness of the public to the state of ecological sustainability.

The original method to calculate national EFs (Wackernagel and Rees, 1996; Monfreda et al., 2004) follows four steps. First, the consumption of a specific population is classified into several major categories, including food, housing, transportation, consumer goods and services. Second, the consumption of each category is converted into the area of different types of land (cropland, forest, pasture, built-up land and energy land) and water-surface appropriated to support consumption. The conversion factors are derived based on world average land productivities. Third, the area of each type of land (per hectare) is normalized into the area of a homogeneous land which has the world average productivity (per global hectare) by using an equivalence factor. The equivalence factor represents the ratio of the world average bio-productivity of each type of land to the world average bio-productivity of all types of land. Finally, the total EFs are calculated by adding up the area of all types of land (using global hectare) and EFs at per capita level are obtained by dividing by the size of population. This method has been used for the National Footprint Account (NFA) and been endorsed by many organizations (Wackernagel et al., 2005; GFN, 2005; WWF, 2006).

There are many debates in the literature on the calculation of EFs (*e.g.* van den Bergh and Verbruggen, 1999; Costanza, 2000; Ayres, 2000; Moffatt, 2000; Opschoor, 2000; van Kooten and Bulte, 2000; Turner et al., 2007; Wiedmann and Lenzen, 2007; Wiedmann et al., 2007). In this paper, we argue that using world average productivities is problematic. In particular, we find that world average productivities do not reflect heterogeneous in-situ impacts induced by the consumption of "like products". For example, the NFA method does not differentiate the ecological impacts of the consumption of 1 kg paddy which is produced by different processes and methods, such as by irrigated land or rain-fed land, by single cropping or multiple cropping, or using organic fertilizers or chemicals, *etc*. Nor does it accurately trace back to the places where the ecological impacts really occur. Though aiming to address consumer responsibility, the neglect of the real linkages between a specific consumption and actual impacts fails to reveal the cause–effect relationship between the two (Zhou et al., 2006). As such, the current NFA may not be an accurate policy indicator at the national and local levels.

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In this paper, we apply the multi-region input–output (MRIO) model at the sub-national level to address several issues with the current NFA approach. These challenges include homogeneous resource and energy intensities used for imports (Kondo, et al., 1998; Lenzen, 1998; Peters and Hertwich, 2006; Tukker and Jansen, 2006; Turner et al., 2007; Weber and Matthews, 2008; Wiedmann, 2009; Peters, et al., 2011), methodological inconsistency in converting primary products and secondary products into EFs (Wiedmann and Lenzen, 2007), and the neglect of the origin of production and spatially diversified ecological impacts. Using MRIO we trace the in-situ impacts that a region exerts on other regions in terms of actual land appropriation. EF accounting at the sub-national level is still limited (see also McDonald and Patterson, 2004; McGregor et al., 2008).

To further address consumer responsibility, we employ a decomposition analysis to identify three consumer behavioral factors, *viz.* the selection of production origins, consumption structure and expenditure level. We demonstrate that each of the three factors plays different roles in influencing regional EFs. By diagnosing the contributions of each factor, we provide customized policy recommendations to achieve effective reduction in regional EFs.

To demonstrate the importance of regional EF accounting, we focus on China. China is selected for two reasons. On the one hand, while China's economy has developed rapidly since the early 1980s, regional inequality in economic development and income level has grown, in particular between the eastern and coastal part and the western part of the country (Han et al., 2007). On the other hand, from an environmental perspective, China's territory covers 49° of latitude and 62° of longitude. Together with mountainous terrain, the natural endowments and bio-productivities vary substantially across the country. These factors contribute to significant local differences in factors of production, yields, lifestyles and diets, *etc.* Regional EF accounting is therefore important since accounting for EF at the national level is unlikely to capture local diversity.

The remaining sections are organized as follows. Section 2 describes the methodology and data. Section 3 presents the results and Section 4 provides policy implications and concludes the paper.

2. Methodology and Data

2.1. Multi-region Input–Output Model for Regional EF Accounting

We apply the Multi-Regional Input–Output Model for China 2000 (hereafter CMRIO) (IDE-JETRO, 2003; CSIC, 2005) to calculate EFs for China's eight regions (Fig. 1). For the explanations on the division of regions, please see IDE-JETRO (2003). Each region is regarded as an open economy trading with other regions within the country and with the rest of the world (ROW). Each regional economy has 30 sectors (Appendix A). Regional EFs consist of three parts: EFs embodied in domestic trade; EFs embodied in imports from ROW; and regional direct land appropriation, such as housing. Our focus is on interregional dependency within the country. To account for EFs embodied in domestic trade, region-specific land productivities and production technologies are used. We do not convert different types of land into generic land based on their relative productivities because each type of land has multiple ecological functions in addition to the provision of biomass and cannot be perfectly substitutable with another.

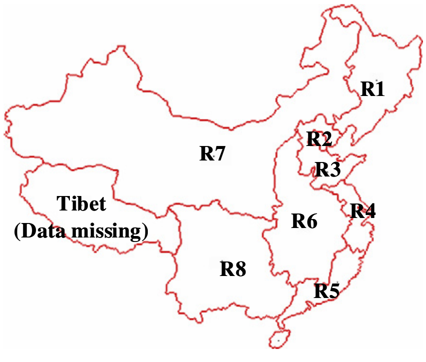
CMRIO is a Chenery–Moses type model based on a regional technical coefficients matrix and an interregional trade coefficients matrix (Chenery, 1953; Moses, 1955; Miller and Blair, 1985). The regional technical coefficients matrix is compiled based on 1997 industry-based input–output tables for the 30 provinces on China's mainland (except for Tibet which data is missing). Interregional trade coefficients are defined as $c_i^{rs} = t_i^{rs}/\sum_r t_i^{rs}$, denoting the proportion of goods i shipped to region s that comes from region r. Interregional trade flows, t_i^{rs}, are compiled by the semi-survey method using the Leontief–Strout gravity model (Leontief and Strout, 1963) and validated by the survey data covering 510 key state enterprises and 100 company groups in China (CSIC, 2005). Data on imports from and exports to ROW are estimated and aggregated based on commodity-based customs statistics for each province. CMRIO is finally obtained by cross-regional balancing against 1997 national input–output table for 30 sectors (see Eq. (1)).

$$\begin{pmatrix} X^1 \\ X^2 \\ \vdots \\ X^8 \end{pmatrix} = \begin{pmatrix} A^{11} & A^{12} & \cdots & A^{18} \\ A^{21} & A^{22} & \cdots & A^{28} \\ \vdots & \vdots & \ddots & \vdots \\ A^{81} & A^{82} & \cdots & A^{88} \end{pmatrix} \begin{pmatrix} X^1 \\ X^2 \\ \vdots \\ X^8 \end{pmatrix} + \begin{pmatrix} \sum_s F^{1s} \\ \sum_s F^{2s} \\ \vdots \\ \sum_s F^{8s} \end{pmatrix} + \begin{pmatrix} E^1 \\ E^2 \\ \vdots \\ E^8 \end{pmatrix} - \begin{pmatrix} M^1 \\ M^2 \\ \vdots \\ M^8 \end{pmatrix} \qquad (1)$$

where X^r: column vector of regional sectoral outputs; A^{rs}: intra-regional (on diagonal) and inter-regional (off-diagonal) input coefficients matrix; F^{rs}: final demand matrix representing final demand in region s supplied by region r; E^r: column vector of regional exports to ROW; M^r: column vector of regional imports from ROW.

CMRIO is an import-competitive type of MRIO, in which domestically produced products and imported “like products” are assumed to be perfectly substitutable for one another. Since our focus is on the interregional dependency within the country, we differentiate domestically produced goods from imported ones by introducing the import ratio matrix, $\hat{M}$ (see Eq. (2)).

$$M = \hat{M}(AX + F) = \hat{M}AX + \hat{M}F \qquad (2)$$



R1: Liaoning, Jinlin, Heilongjiang
R2: Beijing, Tianjin
R3: Hebei, Shandong
R4: Shanghai, Jiangsu, Zhejiang
R5: Fujian, Guangdong, Hainan
R6: Shanxi, Henan, Hubei, Hunan, Anhui, Jiangxi
R7: Inner Mongolia, Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang
R8: Chongqing, Sichuan, Guizhou, Yunnan, Guangxi, Tibet

Fig. 1. China's eight regions and provinces in CMRIO.

where $\hat{M}$ is a diagonal matrix of import ratios, which are defined as $\hat{m}_i^r = m_i^r / \left(\sum_s \sum_j a_{ij}^{rs} x_j^s + \sum_s f_i^{rs} \right)$, denoting the share of imports in total regional demand.

Substituting Eq. (2) for M in Eq. (1), we derive the import non-competitive type MRIO (Eq. (3)), which indicates pure domestic trade relations.

$$X = AX + F + E - \hat{M}(AX + F) = \left[I - \left(I - \hat{M} \right) A \right]^{-1} \left[\left(I - \hat{M} \right) F + E \right] \\ = (I - A^*)^{-1} (F^* + E) = L(F^* + E) \tag{3}$$

$A^* = \left(I - \hat{M} \right) A$ represents domestic input coefficients. $L = (I - A^*)^{-1}$ is the multi-region Leontief inverse and each entry l_{ij}^{rs} indicates the outputs of i in r that is needed to produce one unit final good of j provided by s. $F^* = \left(I - \hat{M} \right) F$ is the final demand supplied domestically.

Pre-multiplying the Leontief inverse L by the diagonal matrix of direct land use coefficients $D(z)$ we obtain the land multiplier matrix $D(z)L$. Each entry $d_i^r(z) l_{ij}^{rs}$ represents the area of land type z appropriated by sector i in r to supply one unit final good of j provided by s. Each $d_i^r(z)$ is region-specific direct land use coefficient denoting the area of land z appropriated in r to produce one unit i. To indicate the interregional dependency on land use, we use Eq. (4) to calculate the total area of land z appropriated in r to satisfy the final consumption in s.

$$EF_{dom}^{rs}(z) = \sum_n \left[\sum_j \left(\sum_i d_i^r(z) l_{ij}^{rn} \right) f_j^{*ns} \right] \tag{4}$$

where f_j^{*ns} represents the final demand of good j in s provided by region n.

CMRIO does not provide data on the origin of imports. Neither does it provide details on the use of imports by regional industries and final consumption. Since this study focuses on domestic trade, we do not make further efforts to disaggregate regional import accounts. We simplify the calculation by using regional direct land use coefficients and consider only direct land appropriation induced by imports (see Eq. (5)). The implied assumption is that imported products are produced the same way as their regionally produced counterparts. We admit that estimation errors occur because regional production recipes, land productivities and land use intensities could be considerably different from those in the origin countries. In addition, indirect land appropriation that is embodied in imports should be taken into account. Using world average land use coefficients could not help solve the estimation errors because the production patterns, land resource endowments and land use practices in the specific origin countries can be greatly different from the world average. For solving this problem, please see Wyckoff and Roop (1994), Lenzen et al. (2004), Nijdam et al. (2005), Peters and Hertwich (2006 and 2008), Webber and Matthews (2007 and 2008), Peters (2008), Peters et al. (2011) and Zhou (2009).

$$EF_{im}^s(z) = \sum_j d_j^s(z) m_j^s \tag{5}$$

Regional EFs of land type z, denoted as $EF^s(z)$, consist of three parts (Eq. (6)): EFs embodied in domestic trade, $EF_{dom}^s(z) = \sum_r EF_{dom}^{rs}(z)$; EFs induced by imports from ROW, $EF_{im}^s(z)$; and regional direct land appropriation, $EF_{dir}^s(z)$, such as housing on built-up land. Regional per capita EFs, notated as $ef^s(z)$, are obtained by dividing by the size of regional population.

$$EF^s(z) = EF_{dom}^s(z) + EF_{im}^s(z) + EF_{dir}^s(z) \tag{6}$$

It should be noted that $EF^s(z)$, in particular the part $EF_{dom}^s(z)$, is the aggregation of the actual area of land z located in different regions. $EF^s(z)$ can be normalized based on the land productivity in each region (see for example Fischer and Sun, 2001). For the purpose of regional analysis, land productivities of the target region can be used as benchmarks to convert different types of land in other regions. This could give local policy-makers a more intuitive figure in terms of local land. However, for the purpose of cross-region comparison, national average land productivities are more appropriate.

2.2. Land Classification and Data

We divide land types into three major categories (see also Wackernagel and Rees, 1996), *i.e.* agriculture land, built-up land and energy land. Agriculture land is further divided into four subcategories (see Table 1). The reference year is 2000.

Energy land is defined as the forests required to sequester human-induced CO_2 emissions. EFs of energy land are calculated by dividing CO_2 emissions by the sequestration factor of forests. In this research, CO_2 emissions are limited to those generated from the combustion of fossil fuels. By comparing the EFs of energy land (the global impacts) with the sequestration capacity of regional forests (the local biological capacity), one can find whether there is a deficit in energy land at the regional level. In our calculation, we use regional forest sequestration factors to highlight the dependency of one region's consumption on the energy land of other regions. To indicate the global impacts of one region's consumption on climate change, regional sequestration factors need to be converted into world average sequestration factor. Wackernagel and Rees (1996) suggested that one hectare of the world average forests could sequester CO_2 emissions from the combustion of 100 GJ of fossil fuels.

The calculation of regional energy land coefficients is conducted by two parallel procedures (see Appendix B). One is the calculation of provincial CO_2 emissions generated from source sectors based on the provincial data of energy consumption using the Guidelines for

Table 1
Classification of land types.

Land types	Explanation	Data sources
1. Agriculture land	Land used by agricultural sector	
Cropland	Land used by crop cultivation	China Agriculture Yearbook Editorial Board (2001)
Forest	Land used by forestry	China Ministry of Forest (1997); China's Natural Resource Series Editorial Board (1995)
Pasture	Prairie or artificial grassland appropriated by stock raising	China Stock Raising Yearbook Editorial Board (2001)
Water surface	Water surface (marine and freshwater) appropriated by fishery	China Agriculture Yearbook Editorial Board (2001)
2. Built-up land	Land appropriated by human settlement, industry and transportation	China Natural Resource Database (2009)
3. Energy land	Forest area required to sequester human-induced CO_2 emissions	Fang, et al. (1998); China National Bureau of Statistics and China National Development and Reform Commissions (2004)

National Greenhouse Gas Inventories (Intergovernmental Panel on Climate Change, 1996). But it should be noted that the provincial data could be under-reported in China's official energy statistics, especially after the year of 1999 due to uncertainty on reporting of township and village mining enterprises (Akimoto et al., 2006; Peters et al., 2007). The other is the calculation of provincial sequestration factors derived from the province-specific biomass of forests (see Fang et al., 1998).

2.3. Decomposition Analysis

Decomposition analysis has been widely used to analyze a change in the output that is caused by the changes in primary factors (Fujimagari, 1989; Forssell, 1989). Since the 1990s, it has been extended to energy analysis (Chen and Rose, 1990; Li et al., 1990; Rose and Chen, 1991; Liu et al., 1992; Lin and Polenske, 1995) and environmental analysis (Torvanger, 1991; Common and Salma, 1992; Ang and Pandiyan, 1997; Chang and Lin, 1998; Wier, 1998; Wier and Hasler, 1999; Munksgaard et al., 2000; Peters et al., 2007; Zhang et al., 2009; Zhang, 2009).

In a matrix version of decomposition analysis, an overall change in the matrix product, $Y = \prod_{i=1}^{n} X_i (n>1)$, can be attributable to the changes in each factor of the matrix X_i. Among others, Betts (1989) provides a summary on five general methods for matrix product decomposition. In this study, we adopted *Method 5* (see Eq. (7)), which applies the mean-value expansion to remove the higher order residual term produced by the Taylor expansion.

$$\begin{aligned}\Delta Y = Y^1 - Y^0 &= \prod_{i=1}^{n} X_i^1 - \prod_{i=1}^{n} X_i^0 \\ &= \frac{1}{2}\sum_{k=1}^{n}\left\{\prod_{j<k} X_j^0 \left(X_k^1 - X_k^0\right)\prod_{l>k} X_l^1\right\} + \frac{1}{2}\sum_{k=1}^{n}\left\{\prod_{j<k} X_j^1 \left(X_k^1 - X_k^0\right)\prod_{l>k} X_l^0\right\}\end{aligned} \tag{7}$$

Regional consumption that provided domestically, *i.e.* F^{*s}, is expressed in the product of three behavioral factors: the selection of the origin of production, consumption structure and expenditure level (Eq. (8)).

$$F^{*s} = \hat{T}^s \times S^s \times Q^s \tag{8}$$

where F^{*s}: regional per capita final consumption (a column vector of 240×1) with each entry f_j^{*rs} representing the per capita final consumption of good j in s provided by r; $\hat{T}^s$: trade mix matrix (240×30) consisting of eight blocks and each block $\hat{T}^{rs}$ being a diagonal matrix (30×30) with each entry $\hat{t}_j^{rs}$ indicating the share in the total final consumption of good j in s that is provided by r; S^s: consumption structure in s (a column vector of 30×1) denoting the share of expenditure on each commodity; Q^s: per capita expenditure in s that is spent on domestically produced commodities (a scalar).

$\hat{T}^s$, S^s and Q^s reflect three aspects of regional consumption: (i) Where are the goods made and how are they produced? (ii) What is consumed? (iii) How much is consumed?

We use the national average levels as the benchmark. The difference between each $ef_{dom}^s(z)$ and the national average $ef_{dom}^{av}(z)$ could be attributable to the differences in three factors between the regional level and the national level (see Eq. (9)).

$$\begin{aligned} ef_{dom}^s(z) - ef_{dom}^{av}(z) &= \bar{D}(z) \times \left(F^{*s} - F^{*av}\right) \\ &= \bar{D}(z) \times \left(\hat{T}^s \times S^s \times Q^s - \hat{T}^{av} \times S^{av} \times Q^{av}\right) \\ &= \bar{D}(z) \times \left\{ \begin{array}{c} \underbrace{\left[\frac{1}{2}\left(\hat{T}^s - \hat{T}^{av}\right) \times S^s \times Q^s + \frac{1}{2}\left(\hat{T}^s - \hat{T}^{av}\right) \times S^{av} \times Q^{av}\right]}_{\text{trade factor}(T-\text{factor})} + \\ \underbrace{\left[\frac{1}{2}\hat{T}^s\left(S^s - S^{av}\right) \times Q^{av} + \frac{1}{2}\hat{T}^{av} \times \left(S^s - S^{av}\right) \times Q^s\right]}_{\text{structure factor}(S-\text{factor})} + \\ \underbrace{\left[\frac{1}{2}\hat{T}^s \times S^s\left(Q^s - Q^{av}\right) + \frac{1}{2}\hat{T}^{av} \times S^{av} \times \left(Q^s - Q^{av}\right)\right]}_{\text{quantity factor}(Q-\text{factor})} \end{array} \right\} \end{aligned} \tag{9}$$

where $\bar{D}(z)$: land multipliers (a row vector of 1×240) with each entry defined as $\bar{d}_j^s(z) = \sum_r \sum_i d_i^r(z) l_{ij}^{rs}$; $ef_{dom}^s(z) = EF_{dom}^s(z)/p^s$: regional per capita *ef* of land *z* that is embodied in domestic trade; $ef_{dom}^{av}(z) = \left(\sum_s ef_{dom}^s(z) \times p^s\right)/P$: national average per capita *ef* of land *z* that is embodied in domestic trade, where p^s and P represent regional population and national population, respectively. Three parts in the square brackets represent trade factor (*T*-factor), structure factor (*S*-factor) and quantity factor (*Q*-factor), respectively.

3. Results

3.1. Regional EF Accounts

Table 2 presents regional accounts of $ef^s(z)$ (see Eq. (6)). National per capita footprints (calculated as $ef^{av}(z) = (\sum_s ef^s(z) \times p^s)/P$) consists of 0.11 ha of cropland, 0.08 ha of forest, 0.17 ha of pasture, 0.005 ha of water surface, 0.02 ha of built-up land and 0.39 ha of energy land. Regional differences in $ef^s(z)$ are 2.8 times for cropland (between *S*1 and *S*4); 8.4 times for forest (between *S*1 and *S*3); 40.3 times for pasture (between *S*7 and *S*4); 3.5 times for water surface (between *S*1 and *S*7); 2.5 times for built-up land (between *S*7 and *S*5); and 2.7 times for energy land (between *S*7 and *S*3), respectively. Among all the regions, an average person in *S*1 has the largest ecological footprints on cropland and forest, an average person in *S*4 has the largest ecological footprints on water surface, and an average person in *S*7 has the largest ecological footprints on pasture, built-up land and energy land.

Table 3 presents the origins of regional EFs. On the one hand, regions *S*2 (Beijing and Tianjin), *S*4 (eastern coastal region) and *S*5 (southern coastal region), the more developed regions in China's economy, are less self-sufficient in land supporting their consumption. On the

Table 2
Regional *ef* accounts for each land type (in ha/cap).

	*S*1	*S*2	*S*3	*S*4	*S*5	*S*6	*S*7	*S*8	National average
$ef^s(crop)$	0.1974	0.0790	0.0841	0.0700	0.0793	0.0872	0.1914	0.1095	0.1067
$ef^s(forest)$	0.2025	0.0350	0.0242	0.0422	0.1024	0.0568	0.1334	0.0892	0.0806
$ef^s(pasture)$	0.0937	0.0985	0.0361	0.0303	0.0414	0.0643	1.2211	0.0961	0.1690
$ef^s(water)$	0.0087	0.0040	0.0037	0.0072	0.0070	0.0054	0.0025	0.0025	0.0050
$ef^s(built\text{-}up)$	0.0390	0.0274	0.0243	0.0222	0.0164	0.0228	0.0418	0.0181	0.0238
$ef^s(energy)$	0.6372	0.7435	0.3007	0.5506	0.3878	0.3230	0.8025	0.3081	0.3913

Table 3
Share in the regional *ef* by the origin of land use (in %).

		*R*1	*R*2	*R*3	*R*4	*R*5	*R*6	*R*7	*R*8	ROW
*S*1	Cropland	91.2	0.1	1.9	0.4	0.3	1.5	1.1	0.3	3.2
	Forest	93.8	0.0	0.5	0.2	0.4	1.0	0.7	0.2	3.1
	Pasture	76.8	0.3	1.3	0.3	0.3	2.2	14.7	0.5	3.6
	Water surface	90.4	0.1	1.8	1.1	0.6	2.2	0.3	0.2	3.3
	Built-up land	92.8	0.1	0.8	0.4	0.2	0.7	0.3	0.1	4.6
	Energy land	87.4	0.2	1.1	0.7	0.3	0.9	0.8	0.2	8.4
*S*2	Cropland	3.5	52.2	9.9	1.0	0.7	5.5	7.8	1.0	18.3
	Forest	8.4	44.4	5.7	1.4	2.2	8.1	12.3	1.8	15.7
	Pasture	1.1	37.2	2.7	0.3	0.2	3.0	41.6	0.6	13.2
	Water surface	3.1	56.1	8.4	2.3	1.3	6.9	1.7	0.4	19.7
	Built-up land	0.8	69.7	3.2	0.5	0.3	2.0	1.0	0.2	22.2
	Energy land	0.7	68.7	4.7	0.7	0.3	3.4	1.3	0.2	20.1
*S*3	Cropland	1.0	0.3	86.1	1.0	0.4	2.8	1.3	0.4	6.7
	Forest	3.7	0.4	74.5	2.1	1.9	6.3	3.1	1.2	6.9
	Pasture	0.9	0.6	65.4	0.9	0.4	4.4	19.9	0.8	6.7
	Water surface	1.0	0.3	83.9	2.5	0.8	4.0	0.3	0.2	6.9
	Built-up land	0.3	0.2	92.3	0.8	0.2	1.1	0.2	0.1	4.7
	Energy land	0.6	0.4	83.6	2.4	0.4	2.1	0.7	0.3	9.6
*S*4	Cropland	1.0	0.2	4.2	76.9	1.5	6.3	1.6	1.1	7.1
	Forest	1.8	0.1	1.8	75.2	3.4	6.9	1.8	1.5	7.5
	Pasture	1.0	0.4	3.3	49.0	1.5	10.1	23.7	2.2	8.8
	Water surface	0.4	0.1	1.7	85.4	1.3	3.9	0.2	0.2	6.7
	Built-up land	0.3	0.1	1.6	84.4	0.7	2.7	0.3	0.3	9.5
	Energy land	0.3	0.1	1.2	80.3	0.8	2.6	0.4	0.3	13.9
*S*5	Cropland	0.7	0.2	2.7	2.0	71.3	8.5	2.2	3.2	9.2
	Forest	0.5	0.1	0.5	0.9	81.3	4.3	1.2	2.0	9.1
	Pasture	0.5	0.3	1.5	0.9	43.0	10.8	28.8	5.1	9.2
	Water surface	0.3	0.1	1.3	2.6	79.2	6.2	0.3	0.8	9.2
	Built-up land	0.2	0.1	1.0	1.3	77.0	3.1	0.3	1.1	15.8
	Energy land	0.2	0.1	0.8	2.0	70.5	3.0	0.5	1.1	21.8
*S*6	Cropland	0.3	0.1	1.8	0.6	0.4	94.5	1.0	0.7	0.7
	Forest	0.5	0.0	0.7	0.6	0.8	94.8	1.1	0.8	0.7
	Pasture	0.2	0.1	0.9	0.4	0.3	85.7	9.4	0.8	2.3
	Water surface	0.2	0.0	1.2	1.0	0.6	96.0	0.2	0.2	0.5
	Built-up land	0.2	0.1	1.2	0.9	0.4	95.1	0.5	0.4	1.3
	Energy land	0.4	0.2	2.0	2.9	1.0	85.4	1.5	1.0	5.6
*S*7	Cropland	0.3	0.1	0.9	0.2	0.2	1.4	93.3	0.5	3.1
	Forest	0.4	0.0	0.4	0.2	0.3	1.3	93.6	0.6	3.1
	Pasture	0.0	0.0	0.1	0.0	0.0	0.2	96.7	0.1	3.0
	Water surface	1.0	0.2	3.1	1.8	1.3	6.7	81.4	0.9	3.8
	Built-up land	0.3	0.1	0.7	0.3	0.2	1.1	94.4	0.4	2.4
	Energy land	0.3	0.1	0.6	0.6	0.3	1.3	91.4	0.5	4.9
*S*8	Cropland	0.2	0.0	0.7	0.2	0.4	1.7	1.3	94.6	0.9
	Forest	0.2	0.0	0.2	0.2	0.7	1.4	1.1	95.3	0.9
	Pasture	0.1	0.0	0.3	0.1	0.2	1.4	9.5	87.3	1.1
	Water surface	0.3	0.1	1.2	1.1	1.6	4.7	0.6	88.9	1.4
	Built-up land	0.1	0.0	0.6	0.4	0.6	1.5	0.5	94.4	1.8
	Energy land	0.2	0.1	0.6	0.9	0.9	2.1	1.0	91.1	3.2

other hand, cropland, water surface, built-up land and energy land in *R*3 (the northern coastal region), forest and pasture in *R*7 (the northwest inland region), and all types of land except for pasture in *R*6 (the central inland region) play important roles in supporting relevant consumption in other regions.

3.2. Decomposition of Regional Ecological Footprints

Table 4 presents the highest and the lowest values of regional land multipliers, indicating sectoral and regional variation in land use intensities. In general, to provide the unit final products, *R*7, *R*8 and *R*1 use more lands than *R*2, *R*4, and *R*5.

Table 5 shows the results of the decomposition of the differences between $ef^{s}_{dom}(z)$ and $ef^{av}_{dom}(z)$ into three factors, *i.e.* *T*-factor, *S*-factor and *Q*-factor. A positive value represents a contribution of a factor to an increase in the difference between the regional level and the national level, while a negative value indicates a contribution of a factor to the decrease of the difference between the regional and the national levels.

Each factor plays different roles in creating the variation between the regional levels and the national average. From the viewpoint of individual factors, *T*-factor is negative for *S*2, *S*3, *S*4 and *S*5 for all types of land (except for water surface for *S*4), indicating that the trade mix factor contributes to reducing the ecological impacts induced by the consumption in these regions than the national average level. *S*-factor is negative for *S*1, *S*2, *S*3 and *S*4 for the four types of agriculture land, and for *S*5, *S*6, *S*7 and *S*8 for energy land, indicating that the consumption structure in these regions works to decrease regional ecological footprints than the national average level. *Q*-factor, the level of expenditure, is negative for less developed inland regions, *S*6, *S*7 and *S*8.

From the total factor point of view, the aggregated effects of three factors on ecological impacts vary from one region to another. *S*3 appropriates less of all land types in supporting its consumption, attributable to a less land-intensive trade mix and consumption structure, and less expenditure compared to other more developed regions (*S*2, *S*4 and *S*5). On the one hand, *S*7 has the lowest *Q*-factor for most of the land types; however the trade mix and the consumption structure are more land-intensive. The mix of these effects leads to the fact that the region apportions the largest area of land for pasture, built-up land and energy land. On the other hand, *S*2 has the highest *Q*-factor for all land types. However, the less land-intensive consumption structure and trade mix greatly contribute to offsetting the impacts of its high-level expenditure on regional ecological footprints. As a result, the EFs of *S*2 are about the national average level, which are much lower than the EFs of *S*7.

4. Policy Implications and Conclusions

In order to reflect regional diversity in ecological footprint accounting, we present a regional approach using the multi-region input–output model. This method enables us to trace the origin of trade and therefore helps account for the ecological consequences embedded in the network of interregional trade. To address both the sectoral and regional differences in land use intensities, we further employ decomposition analysis to show how consumers' behaviors influence regional ecological footprints. Several conclusions follow.

First, the empirical study for China's eight regions indicates that regional per capita EF inventories vary from one region to another in terms of not only the amount of land area but also the mix of different land types. These variations demonstrate that national EF accounting has limitations when addressing region-specific characteristics. Taking account of regional diversity is important to a country like China. EF accounting at the regional level can help customize and prioritize policy recommendations. For example, at the national level, energy and pasture-dependent consumption can be addressed as priorities. While at the regional levels, energy and forest-dependent consumption in *S*1 and *S*5, energy-dependent consumption in *S*2, *S*3, *S*4 and *S*6, energy and cropland-dependent consumption in *S*8, and pasture and energy-dependent consumption in *S*7 could be set as regional priorities.

Second, land multipliers calculated by the MRIO model demonstrate not only sectoral variations but also substantial regional differences in land use intensity. Sectoral differences represent the specific nature of ecological impacts imposed by different goods. Regional differences in land use intensity to provide “like products” are generated by a mixture of regional diversity in land resource endowments, production recipes, technologies, process and production methods, and management practices, *etc.* These support our argument that applying global average land productivities and land use intensities as the conversion factors to the “like products” are not appropriate for accounting at the national and local levels.

Third, though one of the aims of EF accounting generated by NFA is to reflect the ecological impacts embodied in international trade, it cannot trace the origin of land use to specific consumption and therefore fails to address the cause–effect relationships that are at the core of ecological deterioration, such as land degradation and

Table 4
The highest and the lowest value of region-sector-specific land multipliers (in ha/10^6 RMB).

Sector	Cropland		Forest		Pasture		Water surface		Built-up land		Energy land	
	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low
1	180.82	33.25	138.38	12.48	1217.81	3.53	5.61	1.87	1.33	0.44	88.95	18.44
	(*R7*)	(*R5*)	(*R1*)	(*R2*)	(*R7*)	(*R4*)	(*R1*)	(*R8*)	(*R7*)	(*R5*)	(*R7*)	(*R5*)
2	4.11	0.38	3.01	0.20	15.31	0.55	0.25	0.02	5.13	1.02	243.01	51.27
	(*R6*)	(*R2*)	(*R8*)	(*R2*)	(*R7*)	(*R2*)	(*R6*)	(*R2*)	(*R7*)	(*R4*)	(*R5*)	(*R3*)
3	1.83	0.34	1.45	0.21	7.20	0.28	0.07	0.02	3.30	0.64	202.76	47.91
	(*R8*)	(*R4*)	(*R8*)	(*R2*)	(*R7*)	(*R4*)	(*R6*)	(*R2*)	(*R7*)	(*R4*)	(*R8*)	(*R3*)
4	2.68	0.57	2.07	0.31	14.05	0.70	0.14	0.03	6.39	1.22	243.52	56.93
	(*R7*)	(*R2*)	(*R1*)	(*R2*)	(*R7*)	(*R4*)	(*R6*)	(*R2*)	(*R7*)	(*R4*)	(*R2*)	(*R5*)
5	4.15	0.63	3.34	0.33	15.84	0.85	0.21	0.03	5.50	1.32	184.39	32.34
	(*R8*)	(*R2*)	(*R8*)	(*R2*)	(*R7*)	(*R4*)	(*R6*)	(*R2*)	(*R7*)	(*R5*)	(*R7*)	(*R5*)
6	76.35	15.02	56.08	7.33	498.74	5.42	2.36	0.70	4.43	1.14	132.41	28.89
	(*R7*)	(*R4*)	(*R1*)	(*R2*)	(*R7*)	(*R4*)	(*R1*)	(*R8*)	(*R7*)	(*R4*)	(*R7*)	(*R3*)
7	64.68	2.78	45.10	2.89	420.09	2.04	1.39	0.22	4.90	1.37	149.63	32.34
	(*R7*)	(*R5*)	(*R7*)	(*R4*)	(*R7*)	(*R5*)	(*R1*)	(*R5*)	(*R7*)	(*R4*)	(*R7*)	(*R5*)
8	34.00	3.07	23.52	1.45	211.90	2.55	0.84	0.15	5.40	1.41	121.09	24.83
	(*R7*)	(*R2*)	(*R7*)	(*R2*)	(*R7*)	(*R5*)	(*R6*)	(*R2*)	(*R7*)	(*R4*)	(*R7*)	(*R5*)
9	25.86	1.47	18.04	0.76	165.22	1.63	0.36	0.07	5.44	1.65	160.86	41.67
	(*R7*)	(*R2*)	(*R7*)	(*R2*)	(*R7*)	(*R4*)	(*R5*)	(*R2*)	(*R7*)	(*R4*)	(*R7*)	(*R5*)
10	28.90	1.01	20.13	0.51	184.76	1.10	0.43	0.05	5.02	1.37	260.33	37.35
	(*R7*)	(*R2*)	(*R7*)	(*R2*)	(*R7*)	(*R4*)	(*R6*)	(*R2*)	(*R7*)	(*R4*)	(*R7*)	(*R2*)
11	3.24	0.55	2.55	0.30	10.46	0.68	0.10	0.03	5.28	1.52	250.76	52.11
	(*R8*)	(*R5*)	(*R8*)	(*R2*)	(*R7*)	(*R5*)	(*R6*)	(*R2*)	(*R7*)	(*R5*)	(*R8*)	(*R2*)
12	20.32	1.92	14.15	0.96	128.37	1.68	0.34	0.09	5.29	1.44	381.50	61.16
	(*R7*)	(*R2*)	(*R7*)	(*R2*)	(*R7*)	(*R4*)	(*R6*)	(*R2*)	(*R7*)	(*R4*)	(*R7*)	(*R5*)
13	5.10	0.87	3.52	0.48	29.39	1.05	0.15	0.04	5.89	1.73	436.32	84.85
	(*R7*)	(*R2*)	(*R7*)	(*R2*)	(*R7*)	(*R5*)	(*R6*)	(*R2*)	(*R7*)	(*R4*)	(*R7*)	(*R3*)
14	3.12	0.86	2.14	0.47	16.27	1.07	0.11	0.04	6.41	1.99	511.05	90.29
	(*R7*)	(*R2*)	(*R7*)	(*R2*)	(*R7*)	(*R5*)	(*R6*)	(*R2*)	(*R7*)	(*R5*)	(*R7*)	(*R2*)
15	3.30	0.80	2.53	0.45	18.22	1.12	0.11	0.04	5.40	1.80	192.04	64.63
	(*R7*)	(*R2*)	(*R8*)	(*R2*)	(*R7*)	(*R4*)	(*R6*)	(*R2*)	(*R7*)	(*R4*)	(*R7*)	(*R5*)
16	3.31	0.58	2.27	0.32	17.22	0.91	0.11	0.03	6.18	1.60	216.27	46.54
	(*R7*)	(*R2*)	(*R7*)	(*R2*)	(*R7*)	(*R2*)	(*R6*)	(*R2*)	(*R7*)	(*R5*)	(*R7*)	(*R2*)
17	2.95	0.65	2.02	0.36	14.86	0.95	0.10	0.03	5.32	1.63	200.18	41.04
	(*R7*)	(*R2*)	(*R7*)	(*R2*)	(*R7*)	(*R5*)	(*R6*)	(*R2*)	(*R7*)	(*R4*)	(*R7*)	(*R2*)
18	4.38	0.69	3.01	0.38	23.02	1.06	0.12	0.03	6.28	1.71	193.96	43.90
	(*R7*)	(*R2*)	(*R7*)	(*R2*)	(*R7*)	(*R2*)	(*R6*)	(*R2*)	(*R7*)	(*R5*)	(*R7*)	(*R2*)
19	3.53	0.40	2.43	0.22	18.96	0.62	0.10	0.02	5.90	1.32	157.29	21.00
	(*R7*)	(*R2*)	(*R7*)	(*R2*)	(*R7*)	(*R2*)	(*R3*)	(*R2*)	(*R7*)	(*R4*)	(*R7*)	(*R2*)
20	2.42	0.53	2.32	0.28	12.31	0.81	0.12	0.02	5.19	1.41	157.12	29.48
	(*R1*)	(*R2*)	(*R1*)	(*R2*)	(*R7*)	(*R2*)	(*R6*)	(*R2*)	(*R7*)	(*R4*)	(*R7*)	(*R2*)
21	3.23	0.64	2.58	0.35	13.08	0.76	0.10	0.03	5.16	1.39	171.42	34.98
	(*R8*)	(*R2*)	(*R8*)	(*R2*)	(*R7*)	(*R4*)	(*R6*)	(*R2*)	(*R7*)	(*R4*)	(*R7*)	(*R2*)
22	15.59	1.01	10.84	0.54	97.66	1.42	0.28	0.05	4.72	1.46	155.26	30.05
	(*R7*)	(*R2*)	(*R7*)	(*R2*)	(*R7*)	(*R4*)	(*R6*)	(*R2*)	(*R7*)	(*R5*)	(*R7*)	(*R5*)
23	4.20	0.00	3.36	0.00	4.13	0.00	0.11	0.00	3.02	0.27	88.14	2.57
	(*R8*)	(*R1*)	(*R8*)	(*R1*)	(*R8*)	(*R1*)	(*R8*)	(*R1*)	(*R8*)	(*R4*)	(*R8*)	(*R2*)
24	2.40	0.50	1.86	0.28	12.97	0.83	0.11	0.02	5.37	1.48	1826.90	273.01
	(*R7*)	(*R2*)	(*R1*)	(*R2*)	(*R7*)	(*R2*)	(*R6*)	(*R2*)	(*R7*)	(*R2*)	(*R7*)	(*R5*)
25	3.48	0.87	2.39	0.48	18.30	1.42	0.16	0.04	7.51	1.94	678.93	74.29
	(*R7*)	(*R2*)	(*R7*)	(*R2*)	(*R7*)	(*R5*)	(*R6*)	(*R2*)	(*R7*)	(*R5*)	(*R7*)	(*R2*)
26	2.12	0.80	2.04	0.43	9.51	0.77	0.10	0.04	4.22	1.18	334.26	58.64
	(*R1*)	(*R2*)	(*R1*)	(*R2*)	(*R7*)	(*R4*)	(*R5*)	(*R7*)	(*R7*)	(*R4*)	(*R7*)	(*R3*)
27	3.25	0.79	2.59	0.44	16.37	0.97	0.10	0.04	4.82	1.35	198.14	55.44
	(*R8*)	(*R2*)	(*R8*)	(*R2*)	(*R7*)	(*R4*)	(*R6*)	(*R2*)	(*R7*)	(*R5*)	(*R7*)	(*R5*)
28	3.76	0.88	3.44	0.46	20.97	0.65	0.15	0.04	23.74	3.57	217.21	39.39
	(*R7*)	(*R2*)	(*R1*)	(*R2*)	(*R7*)	(*R4*)	(*R1*)	(*R2*)	(*R7*)	(*R2*)	(*R7*)	(*R3*)
29	8.13	0.63	6.09	0.32	48.93	0.63	0.26	0.03	4.65	0.58	133.09	23.17
	(*R7*)	(*R2*)	(*R1*)	(*R2*)	(*R7*)	(*R4*)	(*R1*)	(*R2*)	(*R7*)	(*R5*)	(*R7*)	(*R5*)
30	9.46	0.98	9.66	0.47	55.33	1.13	0.42	0.05	2.75	0.63	117.82	25.16
	(*R1*)	(*R2*)	(*R1*)	(*R2*)	(*R7*)	(*R4*)	(*R1*)	(*R2*)	(*R1*)	(*R2*)	(*R7*)	(*R3*)

deforestation. Our empirical analysis reveals that the multi-region input–output model is more policy-relevant in that it demonstrates which region is responsible for which on-site ecological impacts.

Fourth, underpinning the concept of EF is the objectives of addressing consumer responsibility. This work links consumers' behaviors and the ecological footprints. By decomposition analysis, we uncover the key factors contributing to regional differences in ecological footprints. Table 5 can be used as a checklist for implementing an effective regional reduction policy by addressing those positive values. We find out that not only how much is and what is consumed matter, but also where are the goods made and how are they produced influence the ecological footprints. In contrast to the conventional wisdom that the level of consumption should be constrained, our analysis suggests that harmonizing consumption behaviors is important. Informing people about the geographical indicators (a symbol of the strictness in environmental standards) and the corresponding environmental performance of consumer goods and educating them to choose the lifestyles are therefore important to policymaking.

Table 5
Decomposition of the differences between regional and national *ef*s that embodied in domestic trade (in ha/cap).

	*S*1	*S*2	*S*3	*S*4	*S*5	*S*6	*S*7	*S*8	National average
Cropland									
ef^s_{dom} (crop)	0.1911	0.0646	0.0785	0.0651	0.0720	0.0866	0.1854	0.1085	0.1033
T-factor	0.0660	−0.0380	−0.0149	−0.0570	−0.0593	−0.0050	0.1138	0.0132	
S-factor	−0.0029	−0.0739	−0.0133	−0.0273	0.0080	0.0116	0.0038	0.0314	
Q-factor	0.0246	0.0731	0.0034	0.0461	0.0200	−0.0233	−0.0355	−0.0393	
Total factor	0.0877	−0.0388	−0.0248	−0.0382	−0.0313	−0.0167	0.0821	0.0053	
Forest									
ef^s_{dom} (forest)	0.1963	0.0295	0.0225	0.0390	0.0931	0.0563	0.1292	0.0884	0.0780
T-factor	0.0988	−0.0487	−0.0501	−0.0519	−0.0120	−0.0134	0.0739	0.0163	
S-factor	−0.0031	−0.0500	−0.0072	−0.0199	0.0081	0.0081	0.0027	0.0252	
Q-factor	0.0227	0.0502	0.0019	0.0328	0.0190	−0.0164	−0.0254	−0.0311	
Total factor	0.1184	−0.0485	−0.0554	−0.039	0.0151	−0.0217	0.0512	0.0104	
Pasture									
ef^s_{dom} (pasture)	0.0904	0.0855	0.0337	0.0277	0.0376	0.0628	1.1845	0.0950	0.1644
T-factor	−0.0938	−0.0770	−0.1204	−0.1584	−0.1610	−0.0880	1.1711	−0.0596	
S-factor	−0.0026	−0.1138	−0.0140	−0.0367	0.0100	0.0131	0.0238	0.0359	
Q-factor	0.0224	0.1119	0.0037	0.0584	0.0242	−0.0267	−0.1748	−0.0456	
Total factor	−0.074	−0.0789	−0.1307	−0.1367	−0.1268	−0.1016	1.0201	−0.0693	
Water surface									
ef^s_{dom} (water)	0.0084	0.0032	0.0034	0.0068	0.0063	0.0054	0.0024	0.0025	0.0048
T-factor	0.0026	−0.0016	−0.0009	0.0008	−0.0002	0.0013	−0.0016	−0.0020	
S-factor	−0.0001	−0.0035	−0.0006	−0.0017	0.0005	0.0006	0.0000	0.0010	
Q-factor	0.0011	0.0034	0.0002	0.0029	0.0012	−0.0013	−0.0008	−0.0013	
Total factor	0.0036	−0.0017	−0.0013	0.002	0.0015	0.0006	−0.0024	−0.0023	
Built-up land									
ef^s_{dom} (built-up)	0.0192	0.0168	0.0112	0.0119	0.0082	0.0105	0.0161	0.0079	0.0114
T-factor	0.0053	−0.0060	−0.0006	−0.0059	−0.0053	0.0016	0.0081	0.0011	
S-factor	−0.0001	0.0008	0.0000	0.0004	−0.0001	0.0002	0.0000	−0.0011	
Q-factor	0.0026	0.0106	0.0004	0.0060	0.0022	−0.0027	−0.0033	−0.0035	
Total factor	0.0078	0.0054	−0.0002	0.0005	−0.0032	−0.0009	0.0048	−0.0035	
Energy land									
ef^s_{dom} (energy)	0.5562	0.5611	0.2475	0.4594	0.2840	0.2752	0.6400	0.2612	0.3528
T-factor	0.1237	−0.1866	−0.1209	−0.1162	−0.1387	0.0055	0.4239	0.0449	
S-factor	0.0032	0.0564	0.0044	0.0190	−0.0023	−0.0063	−0.0145	−0.0260	
Q-factor	0.0765	0.3386	0.0112	0.2038	0.0722	−0.0768	−0.1221	−0.1104	
Total factor	0.2034	0.2084	−0.1053	0.1066	−0.0688	−0.0776	0.2873	−0.0915	

From a methodological viewpoint, in addition to presenting the interactions among industrial sectors within an economy, the MRIO model provides a spatial dimension to industries identified by their geographical locations. It is particularly appropriate to analyze the spillover effects and the feedback effects induced by cross-border trade. For an environmental extension of the MRIO model, the hidden ecological impacts embodied in international trade could be estimated systematically. Moreover, MRIO could help analyze localized environmental damages, such as land degradation, that are attributable to off-site consumption of locally produced goods. For example, MRIO could help elucidate the cause–effect relationships between desertification resulting from over-grazing in the Inner Mongolia in China and the increasing demand in meat, leather and cashmere in Beijing and other parts of China. Together with geographical information system (GIS) tools, one can link these relationships and inform relevant policy makers.

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Appendix A

Table A.1
Classification of sectors.

Code	Sector	Code	Sector
1	Agriculture	16	Machinery and equipment
2	Coal mining and processing	17	Transport equipment
3	Crude petroleum and natural gas products	18	Electric equipment and machinery
4	Metal ore mining	19	Electric and telecommunication equipment
5	Non-ferrous mineral mining	20	Instruments, meters, cultural and office machinery
6	Manufacture of food products and tobacco processing	21	Maintenance and repair of machine and equipment
7	Textile goods	22	Other manufacturing products
8	Wearing apparel, leather, furs, down and related products	23	Scrap and waste
9	Sawmills and furniture	24	Electricity, steam and hot water production and supply
10	Paper and products, printing and record medium reproduction	25	Gas production and supply
11	Petroleum processing and coking	26	Water production and supply
12	Chemicals	27	Construction
13	Nonmetal mineral products	28	Transport and warehousing
14	Metal smelting and pressing	29	Wholesale and retail trade
15	Metal products	30	Services

Appendix B

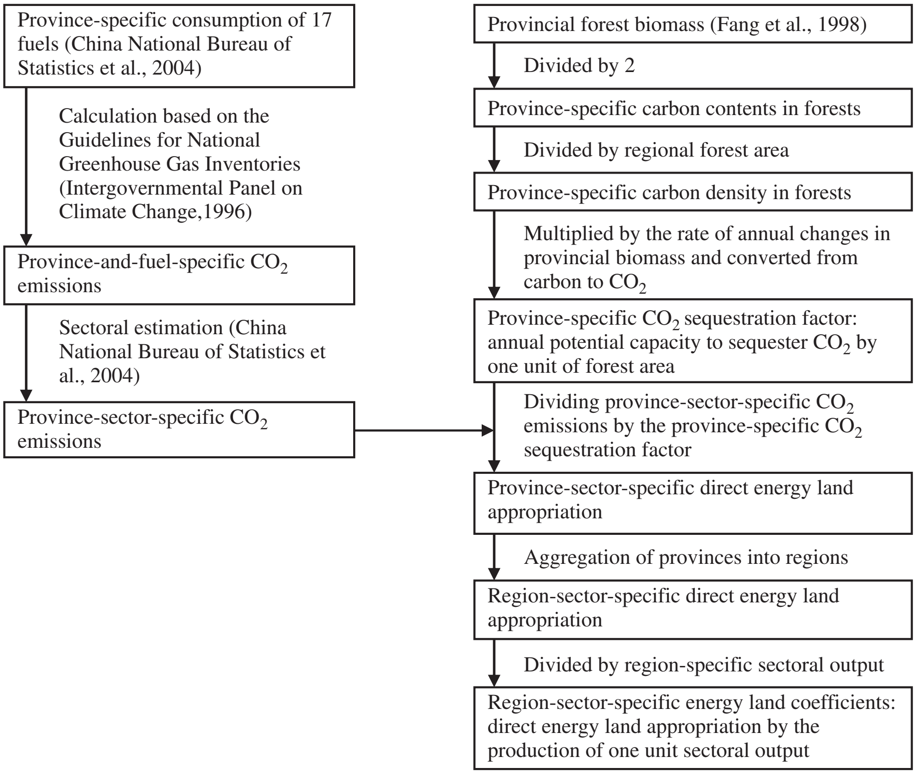

Fig. A.1 Calculation of region-sector-specific energy land use coefficients.

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