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Carbon inequality at the sub-national scale: A case study of provincial-level inequality in CO_2 emissions in China 1997–2007 [☆]

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ABSTRACT

This study asks whether sub-national inequalities in carbon dioxide (CO_2) emissions mirror international patterns in carbon inequality using the case study of China. Several studies have examined global-level carbon inequality; however, such approaches have not been used on a sub-national scale. This study examines inter-provincial inequality in CO_2 emissions within China using common measures of inequality (coefficient of variation, Gini Index, Theil Index) to analyze provincial-level data derived from the IPCC reference approach for the years 1997–2007. It decomposes CO_2 emissions inequality into its inter-regional and intra-regional components. Patterns of per capita CO_2 emissions inequality in China appear superficially similar to, though slightly lower than, per capita income inequality. However, decomposing these inequalities reveals different patterns. While inter-provincial income inequality is highly regional in character, inter-provincial CO_2 emissions inequality is primarily intra-regional. While apparently similar, global patterns in CO_2 emissions are not mirrored at the sub-national scale.

1. Introduction

Inequality between developed and developing regions in greenhouse gas (GHG) emissions, particularly carbon dioxide (CO_2) emissions, has been among the most vexing problems in reaching international agreements on global climate change. Previous studies have shown that national-level CO_2 emissions are strongly and positively correlated with per capita gross domestic product (GDP) (Heil and Wodon, 1997). However past studies of this issue have examined the issue primarily from the scale of the nation-state, ignoring other geographic scales.[1] While addressing inequality at the scale of the nation-state has obvious and immediate ramifications for international climate change negotiations, from an analytical standpoint it fails to address the issue of inequality within the world's largest CO_2 emitting countries. Because of the large size of the world's largest CO_2 emitting countries, variation within these countries have the potential to have a large impact on total global carbon inequality (Duro and Padilla, 2006; Groot, 2010), and understanding the internal dynamics of carbon inequality within these countries has the potential to add significantly to our understanding of total global inequality in CO_2 emissions. As many of these countries continue to develop, internal dynamics of carbon inequality have the potential to shape future energy policies.

This article examines inequality in per capita CO_2 emissions from fossil fuel combustion and per capita GDP at the intra-national scale by examining provincial-level CO_2 emission in China. In doing so it follows several international scale studies that have applied measures commonly used to study income inequality, including the Gini coefficient and Theil Index, to examine the global distribution of per capita CO_2 emissions (Cantore and Padilla, 2010; Duro and Padilla, 2006; Groot, 2010; Heil and Wodon 1997, 2000; Padilla and Serrano, 2006). The provincial-level use of these measures is particularly appropriate within China because inter-provincial economic inequality within China has been studied quite thoroughly using these same measures (Chan and Wang, 2008; Fan, 1995; Fan and Sun, 2008). Provincial differences in per capita GDP in China are both profound, and generally highly regional in their character. Provinces in the Eastern region average 2.5 times the per capita GDP

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[1] Studies of international inequality in CO_2 emissions have, however, examined inequality between supra-national groupings of countries (cf. Padilla and Serrano, 2006).

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of those in the Western region (Fan and Sun, 2008). Because of the parallels between levels of development among regions of China and levels of development between nation-states at the global scale, China provides an ideal test case to examine whether global patterns of inequality in carbon emissions are mirrored at the sub-national scale. One would assume that global patterns of inequality in CO_2 emissions would largely be paralleled on the sub-national scale, with patterns of CO_2 emissions inequality largely paralleling GDP inequality. We will test the veracity of this hypothesis by asking four questions: are per capita CO_2 emissions higher in wealthier regions of China? Are levels of inequality in CO_2 emissions similar to levels of inequality in GDP? Is the composition of measures of inequalities similar? And do these inequalities reflect patterns of regional inequality similar to those seen in GDP? We will examine these questions applying commonly used metrics of inequality to provincial level CO_2 emissions data from China for the period 1997–2007 derived from the Intergovernmental Panel on Climate Change (IPCC) reference approach. This study proceeds as follows: Section 2 discusses previous studies on global inequality in CO_2 emissions and regional inequality in China. Section 3 addresses the methodology, data, and metrics employed in this analysis. Section 4 considers the results of this analysis. Finally, Section 5 presents some concluding remarks.

2. Background

Policies to reduce CO_2 emissions are expected to place economic hardships on nations and individuals, and determining the equity of these burdens is a pressing problem in crafting GHG reduction policies. As a result, differing per capita CO_2 emissions between wealthy and poor countries have become a major sticking point in global negotiations over CO_2 emissions reduction. While variation in per capita CO_2 emissions have been a major source of disagreement between countries, the regional variations in CO_2 emissions *within* countries has remained an unstudied facet of the human dimensions of climate change. This article essays to shed light on the differences in per capita CO_2 emissions between relatively wealthy and relatively poor regions within one country. When comparing CO_2 emissions, most studies focus on per capita CO_2 emissions because they are both readily comparable between countries of different sizes, and readily applicable to a policy goal of equality in CO_2 emissions reduction burdens (Heil and Wodon, 1997, 2000).[2]

2.1. International studies of greenhouse gas inequality

Academic study of the issue of international inequality in carbon emissions was likely first raised by the IPCC's 1996 (Bruce et al., 1996) report on climate change that identified the differing GHG contributions of countries with different economic conditions. Beginning with Heil and Wodon (1997, 2000), several scholars have applied tools generally used to measure income distribution to global CO_2 emissions. Two general types of variation can be seen in this literature. First, scholars have employed different measures of inequality, including concentration measures such as the Gini coefficient and Kakwani Index, and entropy measures such as the Theil and Atkinson indices. The second major variation in this literature is whether data are retrospective, considering historical emissions data, or prospective, modeling the path of future inequality.

The first major technique used to evaluate inequality in CO_2 emissions is the use of concentration indices. Two papers by Heil and Wodon (1997, 2000) employ a group decomposition of the Gini coefficient to explore global inequality in CO_2 emissions. An early paper that drew on historical data (Heil and Wodon, 1997) used a group decomposition of the Gini coefficient based on national per capita income level to illustrate that intergroup variation has been a far more prominent factor in global inequality in CO_2 emissions than within group emission. This illustrated that on a global level per capita CO_2 emissions are directly tied to per capita GDP. In a second paper employing the same technique, Heil and Wodon (2000) project future inequality in CO_2 emissions until 2100. Under their projections, GHG emissions inequality will be reduced, and this reduction will come primarily from decreases in between group inequality. Padilla and Serrano (2006) extend the use of CO_2 emissions concentration indices in measuring inequality in GHG emissions by using a quasi-Gini (which will be described in greater detail in Section 2) that along with the GDP Gini forms the Kakwani Index. Using the quasi-Gini concentration index Padilla and Serrano demonstrate that during their study period (1971–1999), emissions inequality relative to economic inequality was reduced far less than measuring the CO_2 emissions Gini alone would suggest. Groot (2010) has similarly used the Gini Index and the related concept of Lorenz curves to examine the outcome of various forms of carbon reduction policies. This study illustrates that under an outcome of even allocation of carbon emission permits, developed countries would be required to provide the greatest reduction in carbon emissions. Similarly, Cantore and Padilla (2010) have extended this by modeling a wide variety of future emissions reductions scenarios to compare using Gini and Kakwani indices. Their finding suggest that the while emissions will be increasingly progressively distributed under most scenarios (that is CO_2 emissions will be more evenly distributed than GDP), this progressiveness diminishes under scenarios in which a greater burden of reducing emissions is placed on developing countries.

A second major approach to studies of inequality has been to use entropy indices of CO_2 emissions inequality. These studies have the built in advantage of the full decomposability of inequality into its constituent parts, whether by region or industry. Padilla and Serrano (2006) use the Theil Index to decompose the total inequality for global emission, demonstrating that difference between the developed and the developing world are the primary source of inequality. Duro and Padilla (2006) introduce the use of Kaya factors, which decompose CO_2 emissions into the carbon intensity of energy, the energy intensity of an economy, and overall income. This decomposition, while reiterating the general theme of differences between the developed and developing world, also highlights the importance of examining the carbon intensity of the economy. Hedenus and Azar (2005) use a different entropy index, the Atkinson Index, to calculate the split in overall resource consumption, including carbon dioxide. This approach compares a ratio of the wealthiest 20% of the world's population to the poorest 20%. Like several other scholars they show that wealthier areas have substantially higher CO_2 emissions, however this trend appears to be diminishing in the later period of their study.

Several common threads emerge from this research. First, most all studies concur that per capita CO_2 emissions are higher among the wealthiest nations. A second clear trend is that between approximately 1960–2000 this inequality was reduced. Finally, several papers identify the heavy influence of China and India on the results, suggesting a need for further examination of the internal dynamics of CO_2 emissions in those countries

[2] Another metric that may be considered is cumulative per capita emissions (Ding et al., 2009; Zhang et al., 2008). Historical emissions are also greatest from developed countries. While a parallel with the intra-national scale could potentially be interesting, it is beyond the scope of this article.

(Duro and Padilla, 2006; Groot, 2010). While other studies have considered the role of provincial level CO_2 emissions in China (Auffhammer and Carson, 2008; Feng et al., 2009; Qu et al., 2010), as well as variations in energy intensity in China (He and Wang, 2007), to the best of our knowledge none have done so with an explicit goal of examining inequality in CO_2 emissions.

This article contributes to these studies of inequality in carbon emissions by applying frameworks used to understand international inequality in per capita carbon emissions to the distribution of CO_2 emission at the sub-national scale. Previous studies have identified that China and India have a large influence global inequality in CO_2 emissions; we hope to present a more detailed picture of the character of CO_2 emissions of one of these countries. Secondly, by breaking the scalar monopoly of the nation-state in GHG equality analysis, we hope to open the way for broader studies of CO_2 emissions inequality in other regions of the world such as India or nations of the developed world.

However, there are several key differences in considering the inequality at the intra-national and international scales. Nation-states generally have self-contained electricity markets, provinces may not. Indeed in studies of state-level emissions in the United States, trade in electricity contributed to a major difference between CO_2 production and consumption (Aldy, 2005, 2006). Within China, where electrical grids are largely regional in character, provinces are likely to derive portions of their energy from adjacent provinces (Magee, 2006; He and Wang, 2007). One difficulty in this approach is that our data only covers CO_2 production and not consumption. While we recognize this is a shortcoming, we believe that the patterns illustrated are still broadly illustrative of provincial level carbon inequality within China.

2.2. Regional inequality in China

Understanding distribution of CO_2 emissions in China also requires understanding the factors of inter-provincial and inter-regional economic inequality in China. Generally, since reform and opening, the Eastern region of China has been wealthier than the Central and Western regions (Chan and Wang, 2008; Fan, 1995; Fan and Sun, 2008). However, these patterns of inequality in China have changed over time. As the economy of the Eastern seaboard grew rapidly during the 1990s, so did the economic disparities between Eastern and Western regions of China. Studies of regional inequality in China have coalesced around a general pattern that interprovincial inequality in GDP remained steady or declined during the 1980s, increased in the 1990s and leveled off or began declining by the period of the early 2000s. There is some debate as to whether the convergence in equality began in the late 1990s (Chan and Wang, 2008) or in the early 2000s (Fan and Sun, 2008). Using a decomposition of the Theil Index, Fan and Sun (2008) have identified that interregional inequality has been the driving factor in interprovincial income inequality during the 1990s. Other scholars have examined the role of various factors in contributing to regional variations in income inequality in China including the roles of capital investments (Tsui, 2007; Wan and Zhou, 2005) and policy (Fan, 1995). In recent years central government policy has emphasized developing the Western region and revitalizing the Central region of China (Goodman, 2004) to reduce income inequalities. Early results indicate that these policies have stabilized, if not narrowed income inequality between regions (Fan and Sun, 2008).

Defining what constitutes Eastern, Western, and Central regions of China poses another problem. Approaches to regionalization have a long history in geographic studies of China (Cartier, 2002; Cressey, 1934; Skinner, 1985) and while debates about how many regions China has, and what their borders are, it is generally agreed that there are vast differences between different parts of China. In this study we adopt the "three belts" scheme originating in the Seventh Five-Year Plan, illustrated in Fig. 1, which in various forms has been used by recent studies of economic inequality (Fan and Sun, 2008). While official Chinese government regional classifications have since changed, moving Inner Mongolia and Guizhou into the Western region, in this study we will adapt the older regional scheme to preserve comparability with other studies of regional inequality in China (e.g. Fan and Sun, 2008).

The present study contributes to this literature in several ways. First, to the best of our knowledge, no other study has

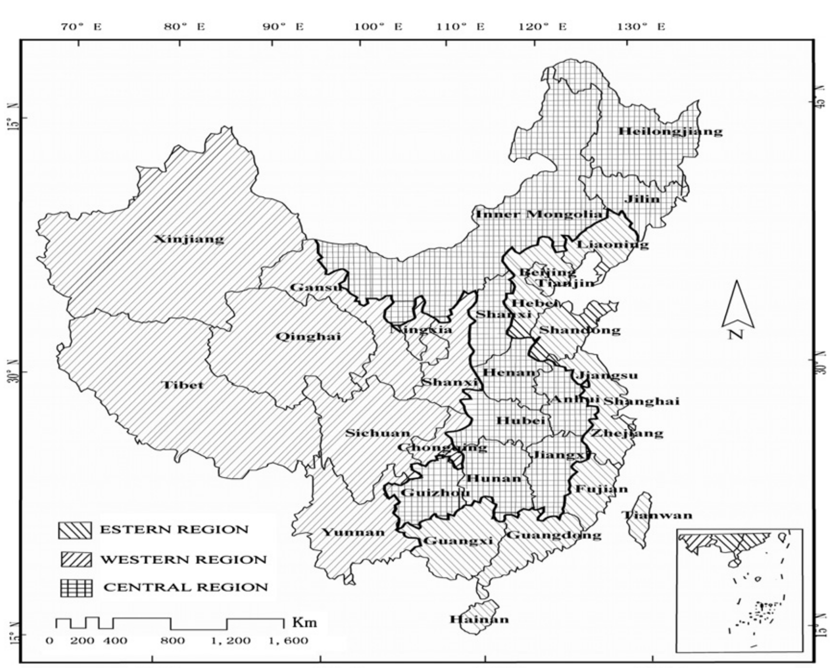

Fig. 1. Regions used in this study.

applied the approaches to CO_2 emission inequality used on a global scale to the sub-national scale. While a clear pattern linking CO_2 emissions to GDP can be seen on a global scale, we hope to test whether similar connections can be seen on a sub-national scale. Similarly, studies of income inequality in China have previously not considered the environmental dimensions of development (notable exceptions being He and Wang (2007) and Poon et al. (2006)). Meanwhile, while the literature on decomposition of CO_2 emissions in China is quite rich (Fan et al., 2007; Zhang et al., 2009; Wang et al., 2005), to our knowledge no studies have examined CO_2 emissions in China from the perspective of CO_2 emissions inequalities. We hope to contribute to this literature by seeing whether regional patterns of income inequality are similarly mapped in environmental impact. A clear pattern of wealthier countries emitting more GHGs exists at the global scale, and similar pattern of economic inequality exists at the sub-national scale in China. Notwithstanding the aforementioned differences between global and national level energy markets, in this study we ask whether China's internal GHG emissions disparities mirror those of the globe? We begin this analysis with four basic questions: are per capita GHG emissions higher in wealthier regions of China? Are levels of inequality in GHG emissions inequality similar to levels of inequality in GDP in China? Is the composition of inequalities similar? And do these inequalities reflect patterns of regional inequality similar to those seen in GDP?

Table 1
Coefficients for fuels used in IPCC reference approach.

Fuel	NCV(e_i)	CEF(c_i)	OC(o_i)/CSR(s_i)
Liquid fossil			
Primary fuels			
Crude oil	42.62	20	0.98
Secondary fuels			
Gasoline	44.8	18.9	0.98
Kerosene	44.67	19.55	0.98
Diesel oil	43.33	20.2	0.98
Fuel oil	40.19	21.1	0.98
LPG	47.31	17.2	0.98
Naphtha	45.01	20	0.8
Bitumen	40.19	22	1
Lubricants	40.19	20	0.5
Other oil	40.19	20	0.98
Solid fossil			
Primary fuels			
Crude coal	20.52	24.74	0.90
Secondary fuels			
Cleaned coal	20.52	24.74	0.90
Other washed coal	20.52	24.74	0.90
Briquettes	20.52	24.74	0.90
Coke oven	28.2	29.5	0.97
Coal tar	28.0	22	0.75
Gaseous fossil			
Natural gas	48	15.3	0.99

3. Data and methods

3.1. Method

CO_2 emissions generate from the combustion of fossil fuels were taken as a proxy for total GHG emissions.[3] Analysis was conducted in two steps. First, CO_2 emission estimates for each province were obtained using the IPCC reference approach (Intergovernmental Panel on Climate Change (IPCC), 2006) and were calculated using

$$T_{CO_{2_{ij}}} = \sum_{i=1}^{n} \left\{ \left[A_{ij} e_{ij} c_{ij}\right] \times 10^{-3} - S_{ij} \right\} o_{ij} \times \frac{44}{12} \quad (1)$$

where n is the number of provinces (27), A_{ij} is the Apparent Fuel Consumption of the ith fuel in the jth province, e_{ij} is the Net Calorific Values (NCV) of the ith fuel, c_{ij} is the Carbon Emission Factors (CEF) of the ith fuel, o_{ij} is the ith fuel's fraction of carbon oxidized (OC). S_{ij} is the stored carbon of the ith fuel in the jth province. The coefficients of each fuel type are presented in Table 1. These data were then used to calculate a variety of inequality measures for GHG emissions and GDP in China detailed in Section 3.3.

3.2. Data

Our analysis compares two types of data: per capita CO_2 emissions and per capita GDP. GHG emissions were calculated from data on energy consumption from the China Statistical Energy Yearbook, published by the China statistics bureau (NBS (National Bureau of Statistics of China), 1997–2007a). These data were processed through the IPCC reference approach (IPCC, 2006) to yield annual estimates of provincial GHG emissions. Data on population and GDP were derived from the statistical yearbooks for each year (NBS, 1997–2007b). Although often considered a problematic metric of development, GDP per capita was selected as the best available measure of affluence because it is the most widely used measure of prosperity, data are readily available, and using this measure affords comparability with both previous studies of both GHG and economic inequality.

Several problems were present with the data available. Others have detailed the difficulties inherent in using population and economic data in China (Fan and Sun, 2008), and these discussions need not be rehashed here. Problems also arose in the data provided for energy consumption. Of China's 34 provincial level administrative divisions, reliable data could be obtained for 27. Macau, Hong Kong, and Taiwan do not use PRC data collection policies. In our sources detailed data on energy consumption were unavailable for Tibet,[4] and were not available for all years for Ningxia. Internal inconsistencies in data for Shanxi and Hainan indicated that these data were likely unreliable due to data collection practices.[5] We selected a time frame of 1997–2007 based on the availability of data. Finally, data were not available below the provincial scale. Thus this analysis considers averages for a province, and does not consider inequalities between individuals in their CO_2 emissions. One likely source or significant

[3] Using net CO_2 from fossil fuel was chosen based on the availability of data. Using this approach fails to account for impact of net changes is forest cover and fuel wood combustion, as well as other greenhouse gasses. However, we were unable to find such data that were comparable between provinces. While biomass is a widely used fuel source, it has not been considered in this study because data on biomass use at a national scale in China is not readily obtainable. While elsewhere in the world deforestation is a major contributor to net GHG emissions, China is currently experiencing net afforestation at the national scale.

[4] For this reason, studies of regional inequality in China commonly exclude Tibet (Fan and Sun, 2008; Chan and Wang, 2008)

[5] This belief was based upon wide inconsistencies between years in the data. In short, multi-year energy consumption data for these two provinces were not autoregressive. The origins of inconsistencies arising in Hainan are unclear, but also of less impact due to Hainan's small size. Inconsistencies arising in Shanxi, a major coal-producing region, have several potential origins. During the study period, in a successful effort to reign in mine fatalities, a large number of small coal mines were shut down and operations consolidated in larger, state owned companies. It is unclear what the results of this may have been for data gathering. Additionally, storage of coal inventories may have been a factor in apparently widely swinging coal consumption.

inequality is between urban and rural areas, which we do not have a ready way of calculating.

3.3. Inequality measures

There are several ways to measure inequality, each of which has unique advantages and drawbacks. We have focused on measures of dispersion, concentration, and entropy: the coefficient of variation (CV); Gini coefficient and Kakwani Index; and Theil Index, respectively.

The simplest of these measures is the CV, which is readily intelligible, but sensitive to outliers. The CV of per capita emissions represents the standard deviation divided by the average per capita emissions of all provinces and is calculated as follows:

$$CV = \frac{\sqrt{\sum_{i=1}^{N}(y_i - \bar{y})^2/N}}{\bar{y}} \quad (2)$$

where y_i is the per capita CO_2 emissions of province i. N is the number of provinces and $\bar{y}$ is the mean per capita CO_2 emission of all provinces. Following Fan and Sun (2008) we have used the unweighted CV that better represents disparities between regions, rather than the weighted CV, which better represents disparities between individuals.[6]

The Gini coefficient is widely understood, and it easily understandable because it is based on a scale of 0–1. However, it has several disadvantages: while expressing total inequality, it does not allow one to see what the shape of inequality is, nor is it completely decomposable between regions or industries. The Gini Coefficient for per capita CO_2 emissions is calculated as follows:

$$G_{ghg} = \left[\frac{2}{N\sum_{i=1}^{N} ghg_i}\sum_{i=1}^{N} i \cdot ghg_i\right] - 1 - \frac{1}{N} \quad (3)$$

where N is the number of provinces and ghg_i is the per capita CO_2 emissions of the ith province, ordered by per capita CO_2 emissions.

A second concentration measure that we have employed is the Kakwani Index. The Kakwani Index compares the concentration of two phenomena, usually GDP and something else, using the same rank ordering. We have calculated the CO_2 Kakwani comparing the per capita GDP and per capita CO_2 emissions. To determine the Kakwani Index we must first calculate a quasi-Gini coefficient of per capita CO_2 emissions in which cumulative CO_2 emissions are ranked by provincial income, rather than provincial GHG emissions. The Kakwani Index represents the difference between the concentration of per capita GDP and per capita CO_2 emissions. The difference between the per capita GHG quasi-Gini coefficient and the per capita income Gini coefficient represent the Kakwani Index (Cantore and Padilla, 2010; Padilla and Serrano, 2006). Thus a negative number indicates that GHG emissions are less concentrated (more equally distributed) than income, while a positive number indicates that GHG emissions are more concentrated (less equally distributed) than income.

The Kakwani Index is calculated as follows:

$$K = qG_{ghg} - G_i \quad (4)$$

where G_i is the Gini Index for income, and qG_{ghg} is the quasi-Gini Index of CO_2 emissions. The Gini Coefficient for per capita income is calculated as follows:

$$G_i = \left[\frac{2}{N\sum_{i=1}^{N} y_i}\sum_{i=1}^{N} i \cdot y_i\right] - 1 - \frac{1}{N} \quad (5)$$

where N is the number of provinces and y_i is the per capita income of the ith province, ordered by per capita GDP.

The quasi-Gini Index for CO_2 emissions is calculated as follows:

$$qG_{ghg} = \left[\frac{2}{N\sum_{i=1}^{N} ghg_i}\sum_{i=1}^{N} i \cdot ghg_i\right] - 1 - \frac{1}{N} \quad (6)$$

where N is the number of provinces and ghg_i is the per capita CO_2 emissions of the ith province, ordered by per capita GDP.

The Theil Index, while less readily understood, is completely decomposable without an error term, allowing an examination of the regional composition of inequality. The Theil Index is a weighted entropy index and is calculated as follows (Conceição and Ferreira, 2000):

$$T_{ghg} = \sum_{i=1}^{N} y_i \log(y_i/x_i) \quad (7)$$

where y_i is the portion of total CO_2 emissions of the ith province to the total CO_2 emissions of all sampled provinces and x_i is the portion of total population of the ith province to the total population of all sampled provinces, and N is the number of provinces.

This is decomposed into between region and within region components as follows:

$$T_{ghg} = T_{ghg(br)} + T_{ghg(wr)} \quad (8)$$

where $T_{ghg(br)}$ equals the total between region contribution to the Theil Index and $T_{ghg(wr)}$ equals the total contribution to the Theil Index from within regions. $T_{ghg(br)}$ is calculated as follows:

$$T_{ghg(br)} = \sum_{r=1}^{N} y_r \log(y_r/x_r) \quad (9)$$

where y_r is the portion of total CO_2 emissions of the rth region to the total CO_2 emissions of all regions and x_r is the portion of total population of the rth region to the total population of all regions, and N is the number of regions.

$T_{ghg(wr)}$ is calculated as follows:

$$T_{ghg(wr)} = \sum_{r=1}^{N} w_r \sum_{i(r)=1}^{N} y_{i(r)} \log(y_{i(r)}/x_{i(r)}) \quad (10)$$

where w_r is a weighting of the portion of total CO_2 emissions of rth region as a portion of total CO_2 emissions, $y_{i(r)}$ is the portion of total CO_2 emissions of the ith province in the rth region to the total CO_2 emissions of the rth region and $x_{i(r)}$ is the portion of total population of the ith province the rth region to the total population of the rth region, and N is the number of provinces within the rth region.

For the CV and Theil Index, indices of GDP inequality were calculated by substituting GDP for per capita CO_2 emissions, in the case of the CV (Eq. (2)), and total CO_2 emissions, in the case of the Theil Index (Eq. (7)).

4. Results

Several trends are clear by analyzing changes in these indicators of inequality. First, the wealthier Eastern region of China does exhibit higher levels of CO_2 emissions. Second, levels of inequality in per capita CO_2 emissions are generally superficially similar, but slightly lower than inequality levels in GDP. Third, while levels are similar, concentration indices reveal that CO_2 emissions and GDP share similar levels of concentration, they are concentrated in different provinces. Fourth, interregional GHG inequality constitutes a smaller portion of total interprovincial inequality than intraregional inequality: interprovincial variation in per capita

[6] Using the unweighted CV allows for compatibility with other studies of inequality in China. We have used a weighted measure by including the Theil Index.

emissions originates primarily within regions. This is in direct contrast to regional patterns in GDP inequality. Two caveats should be considered in this comparison. First, as mentioned above, relatively integrated electricity markets make domestic scale CO_2 emissions inequality somewhat messier than global scale emission. Second, because data are available at the provincial level this analysis does not account for differences in CO_2 emissions between individuals.

4.1. Changes in regional emissions over time

It is clear that over the past decade per capita CO_2 emission in China have risen rapidly. This can be seen in Fig. 2, which tracks the average emissions of each region as well as the national average for all provinces for the decade of study. Two patterns are clear from this graph. First, over time emissions have increased, but that increase occurred primarily after 2002. Prior to 2002, all regions showed at most minor increases in per capita CO_2 emissions. After 2002, all regions showed marked increases. The second clear pattern is that Eastern provinces have, on average, higher emissions than Central or Western provinces. This conforms to the general pattern that areas with higher incomes also produce higher level of emissions, however, as we will illustrate below, these patterns do not simply mirror global patterns.

4.2. CO_2 emissions and income inequality

Fig. 3 illustrates changes in Gini, CV, and Theil Index for CO_2 emissions and GDP from 1997 to 2007. Two patterns are visible in these data. First, each of these measures of provincial CO_2 emissions inequality is similar to, but slightly lower than income inequality for the same time period (Fig. 3): in only one year were any of the indices of CO_2 emissions inequality greater than indices of GDP inequality. A second pattern of these data is that measures of GDP and CO_2 emissions inequality do not appear to have similar temporal patterns of change over the course of the decade. During the period during which CO_2 emissions inequality was falling (2000–2004), GDP inequality was actually rising. All three measures of CO_2 emissions inequality roughly showed a similar pattern: from 1997 to 1998 levels of CO_2 emissions inequality remained more or less static, from 1999 to 2002 rose and then fell, and settled back to levels slightly lower than where they began by 2005. While different inequality measures picked up varying degrees of this pattern, the pattern was consistent across measures. This pattern is most pronounced in the coefficient of variation, which is most sensitive to outliers. It is also interesting that the period of growth in CO_2 emissions inequality actually coincided with a period of relative stability in average per capita emissions (1998–2002).

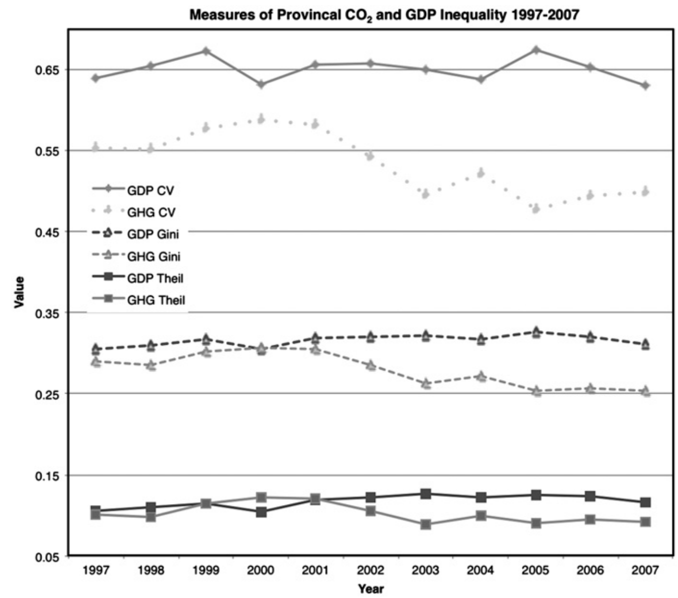

Fig. 3. Measures of GHG and GDP inequality in China 1997–2007.

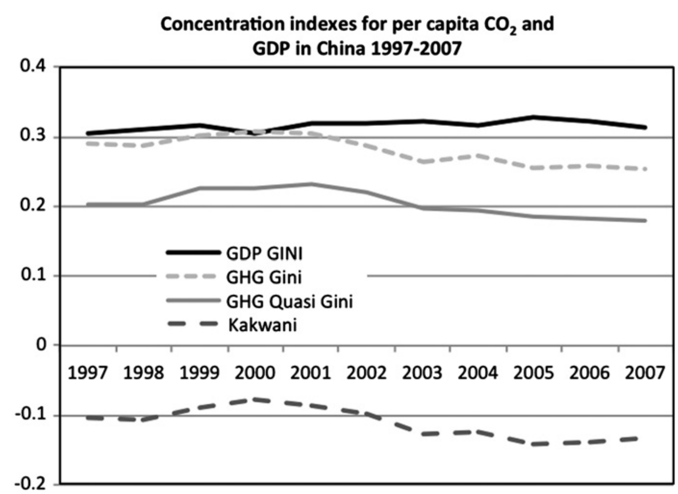

Fig. 4. Concentration indexes for per capita GHG and GDP in China 1997–2007.

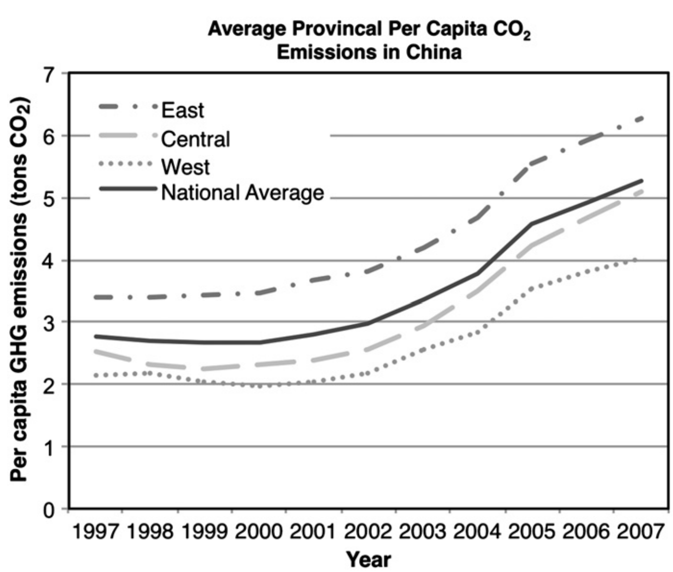

Fig. 2. Average annual per capita GHG emissions 1997–2007.

While levels of CO_2 emissions inequality appear similar to, though slightly lower than GDP inequality, thorough examination of concentration indices, as well as a regional decomposition of the Theil Index, reveal significant differences.

4.3. Concentration indices

While Gini coefficients for interprovincial CO_2 emissions and GDP inequality in China appear similar throughout the study period (Fig. 4), the Kakwani Index illustrates that there are significant differences. The per capita CO_2 quasi-Gini coefficient was consistently lower than the per capita GDP Gini coefficient, and lower by a much larger amount than the CO_2 Gini. The result is that provincial level per capita CO_2 emissions in China have displayed negative Kakwani indices, indicating that

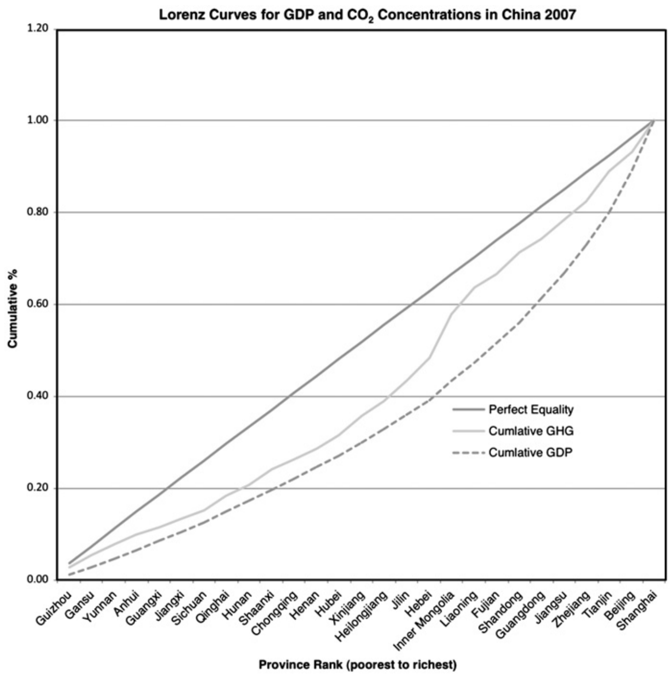

Fig. 5. Lorenz curves for per capita GDP and per capita GHG, 2007.

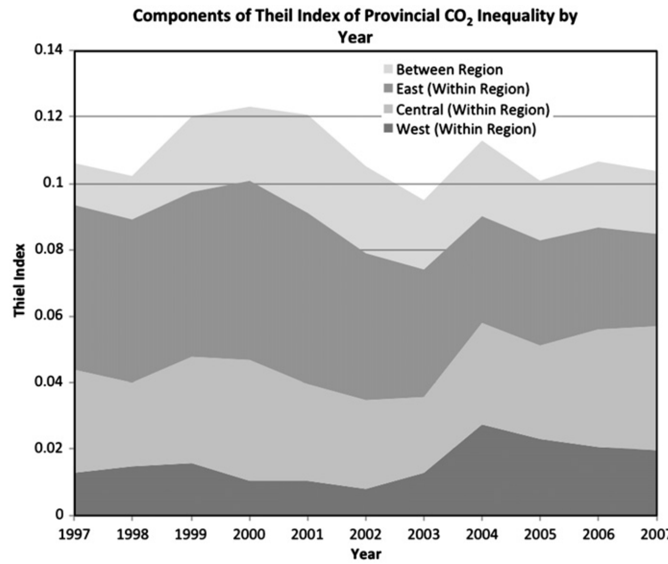

Fig. 6. Components of Theil Index of GHG inequality by year.

CO_2 emissions in China are more evenly distributed between provinces than is income. Fig. 5 illustrates this point using the Lorenz curves for per capita GDP and the per capita CO_2 emissions used to calculate the Kakwani Index in for 2007. The Lorenz curve for per capita CO_2 emissions is notably closer to a perfectly even distribution than the Lorenz curve for per capita GDP. This yields a negative Kakwani Index (-0.16) indicating that per capita CO_2 emissions are less concentrated than per capita income. From the Lorenz curve we can also find the influence of individual provinces, particularly Inner Mongolia, on the total concentration of per capita CO_2 emissions.

There are three implications of a negative and decreasing Kakwani Index in China. First, China's domestic Kakwani Index mirrors worldwide patterns from the late 1970s through late 1990s of negative Kakwani indices for CO_2 emissions (Padilla and Serrano 2006). However, we have been unable to find studies using more recent data on the global level, and therefore cannot make a direct comparison for the same time period.[7] Second, if provincial per capita CO_2 emissions are more evenly distributed than per capita GDP, this indicates that those provinces at the higher level of GDP also have lower carbon intensities (tons CO_2 per unit of GDP). This finding potentially supports the notion that environmental Kuznets curves (Aldy, 2005; Poon et al., 2006) apply to CO_2 emissions in China; however, total emission in more developed regions of China are still higher than in less developed regions. Third, because the Kakwani Index has actually decreased over time (though it rose at the end of the decade) differences in carbon intensity between poor and rich regions are actually increasing as time goes on. This may indicate that provinces with the highest GDP have entered a phase of development where economic development may occur with relative little additional CO_2 emissions. It is worth noting that the period during which the Kakwani Index decreased (2002–2006), was the same period during which total measures of inequality settled into a relatively lower level, and overall emissions increased markedly. This illustrates that these lower levels of inequality were likely driven by increased per capita emissions in lower income provinces, as well as carbon efficiency gains in wealthier provinces.

[7] For the two years with which our study overlaps with Padilla and Serrano the global GHG Kakwani Index was actually positive.

4.4. Intra-regional and inter-regional variation in inequality

Decomposing the Theil Index by region indicates that although interprovincial inequality in GDP and GHG emissions appear similar, their regional characters are quite different, and differs from global patterns in GHG inequality. Although the Eastern region has consistently exhibited higher per capita CO_2 emissions than other regions, this masks large differences in per capita CO_2 emissions within Eastern China, a regional decomposition analysis of the Theil Index reveals that interregional contributions to per capita CO_2 emissions inequality have been relatively low. In the period from 1997 to 2007 interregional inequality has consistently contributed much less than intra-regional inequality (Fig. 6) to the CO_2 inequality Theil Index. In contrast, the Theil Index for GDP inequality within China comes primarily from interregional factors (Fig. 7). Fig. 6 illustrates that throughout the decade studied, the interregional component of the per capita CO_2 Theil Index contributed to between 0.01 and 0.03 of a total index of 0.09–0.12, while during the same period the interregional component of the GDP Theil was from 0.06 to 0.08 of a total index of 0.10–0.13 (Fig. 7). These findings are important because they illustrate a significant difference in the composition of interprovincial inequality in carbon emissions when compared to interprovincial inequality in income. Although interprovincial variation in per capita carbon emissions mirrors interprovincial variation in per capita income absolute levels, GDP inequality is primarily regional in nature, while CO_2 emissions inequality is not. This decomposition of the Theil Index can be contrasted with Padilla and Serrano's (2006) decomposition of the Theil Index at the global scale that showed that most global GHG inequality is derived from differences between rich and poor countries. Taking the Eastern and Western regions of China as the sub-national analog of developed and developing nations, it is clear intra-national CO_2 inequality differs in character from international CO_2 inequality.

The intra-regional components of the Theil Index can be further decomposed into contributions by region. For both GDP and CO_2 emissions the Eastern region began as the largest contributor in intra-regional inequality. In the case of GDP

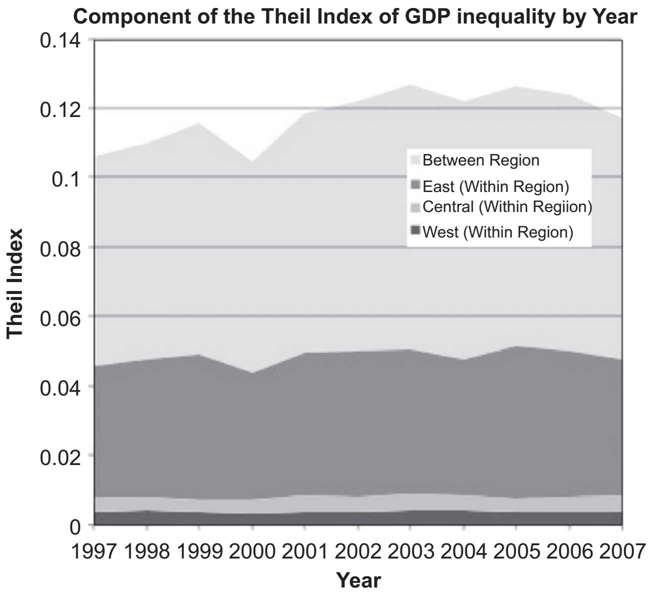

Fig. 7. Components of Theil Index of GDP inequality by year.

inequality, the pattern continued throughout the decade (Fig. 7). However, in the case of CO_2 emissions inequality, over the course of the study period, the Eastern and Central regions traded places in providing the largest contribution, though both remained significant (Fig. 6). What is interesting is the relatively low contribution to total intra-regional inequality contributed by the Western region.[8] The relatively lower population of Western China can partially explain its lower contribution to the Theil Index. Because the Theil Index is weighed according to the share of each provinces CO_2 contribution, there is a limit to how large a contribution a sparsely populated province can make, regardless of its variation from the mean. Thus, the largest contributions interprovincial variations in per capita CO_2 emissions were derived from variation within two of the regions that cumulatively account for 77% of China's population. Also of note, the Eastern region showed a consistent pattern of declining intraregional variation in CO_2 emissions, falling by roughly half during the course of the decade. This is the only components of Theil Index that fell consistently over the study period, and this was likely due to more provinces in the Eastern region converging at both higher levels of CO_2 emissions and lower carbon intensities.

5. Discussion and conclusions

We now return to the four questions with which we began this analysis: are per capita CO_2 emissions higher in wealthier regions of China? Are levels of inequality in CO_2 emissions similar to levels of inequality in GDP? Is the composition of inequalities similar? And do these CO_2 emissions inequalities reflect patterns of regional inequality similar to those seen in GDP?

Our results indicate that GHG emissions in wealthier regions are higher than in less wealthy regions of China. Moreover, at a national scale, interprovincial levels of inequality in per capita CO_2 emissions are similar to, but slightly lower than inequality in per capita GDP. However examining the character of those inequalities reveals a more complex picture in two ways. First, the Kakwani indices indicate that while the Gini coefficient of CO_2 emissions and per capita GDP shared similar levels of concentration during the study period, they were concentrated in different provinces. Second, a regional decomposition indicates that while much of interprovincial income inequality comes from differences between regions, interprovincial CO_2 inequality originates primarily within regions.

When comparing concentration measures of per capita GDP and CO_2 emissions, the Gini indices of the two measures appear similar, but on closer investigation are quite different. This difference is revealed by the Kakwani Index, which was consistently negative (indicating progressive distribution of emissions relative to income), throughout the study period. This discrepancy between the Gini values for per capita income and quasi-Gini value for per capita CO_2 emissions can be understood because the provinces that account for higher levels of concentration are not the same for both CO_2 and GDP. Certain lower income provinces, most notably Inner Mongolia, have quite high levels of GHG emissions relative to their GDP. Inner Mongolia is also among the larger coal producers in China, indicating that regional differences in energy sources may play a role in such inequality. This can be understood by examining the carbon intensity of different provinces in China. Fig. 8 illustrates the carbon intensity relative to GDP of each province in 2007. A clear pattern is evident that provinces with higher per capita GDP also exhibit lower levels of carbon intensity. This pattern of diminishing carbon intensity results in higher levels of concentration of CO_2 emission at the lower end of the GDP scale. As we can see from Fig. 8 these provinces at the lower end of the scale also tend to be those in the Western and Central provinces.

Carbon intensity also plays a central role in differences between GDP and CO_2 in regional patterns of inequality. The higher average incomes in the Eastern region, combined with decreasing carbon intensity with higher levels of income help to explain why interregional inequality contributes relatively less to total interprovincial inequality in CO_2 emissions than inequality in per capita GDP. Although the Eastern region is much wealthier, it also uses GHG producing fuels much more efficiently, resulting in similar per capita emissions. This is a direct outgrowth of greater energy efficiency in Eastern provinces demonstrated by other scholars (He and Wang, 2007). Thus the total emissions share for the region as a whole differ little from its total population share.

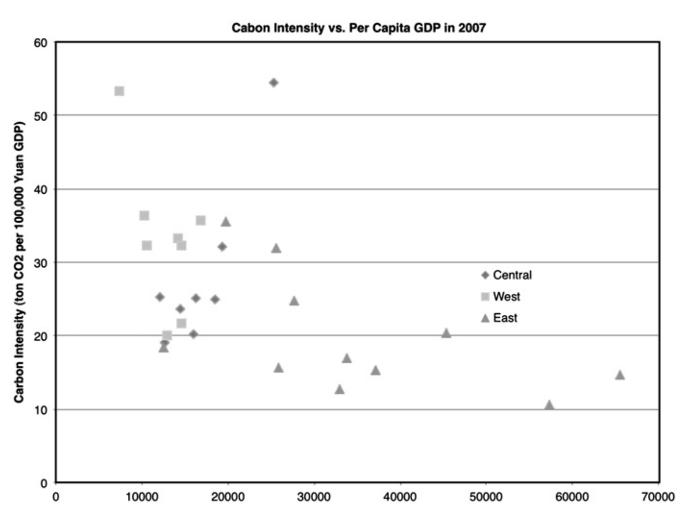

Fig. 8. Carbon intensity compared to per capita GDP, 2007.

[8] We conducted a sensitivity analysis of regionalizations to examine the effects of differing regionalization schemes the Theil contributions. In all cases interprovincial contributions remained constant. However, when adding Inner Mongolia to the Western region a large amount of the intra-regional contribution of the Central region was shifted to the Western region. Other adjustments, such as moving Guizhou into the Western region, had no discernible impact. We hypothesize that Inner Mongolia's large negative entropy in this case is due to a relatively low population, and a large portion of energy intensive industries.

It can be surmised then, that variations in carbon intensity, as well as variations in per capita GDP, play a central role in interprovincial variation in CO_2 emissions. This accords with the general IPAT model of resource use: Impact = Population × Affluence × Technology. In this case impact is carbon emissions. We have accounted for population and affluence, and carbon intensity is a passive measure of technology (Feng et al., 2009). The contributing factors to variations in carbon intensity are outside the scope of this study, but point towards several potentials directions for future research on provincial CO_2 emissions inequality in China. First, a more thorough investigation of variations in CO_2 intensity is called for. Second, following Duro and Padilla (2006) a decomposition of provincial CO_2 emissions by Kaya factors could separate the impact of the energy intensity of provincial economies from carbon intensity of individual fuel sources. The causes of such variations in carbon intensity will be important to identify if China is to achieve its goal or reducing carbon intensity by 40–45% from 2005 levels by 2020 (Wong et al., 2009). The presence of relatively high carbon intensities in China's less developed provinces indicates that internal technology transfer mechanisms to provide clean technology to Western provinces may be called for.

By decomposing China's emissions by region, we have shown there is significant variation in CO_2 emission across regions in China. However, we have also shown that these regional variations are of less importance than the variation within regions. This is in contrast to differences in GDP, which are primarily found between regions. The evidence we have presented demonstrates that global patterns of how of the relationship between GDP and GHG inequality do not directly map onto the subnational scale. The per capita CO_2 emissions of China's provinces are related to per capita GDP, as are the per capita of emissions on the global scale; however, unlike patterns at the global scale, per capita CO_2 emissions seem to have consistently been progressively distributed relative to GDP. Moreover, regionalized patterns of economic inequality in China do not translate directly into patterns of carbon inequality.

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