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Spatial effects of carbon dioxide emissions from residential energy consumption: A county-level study using enhanced nocturnal lighting

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HIGHLIGHTS

- We evaluate carbon dioxide emissions from residential energy consumption (REC) at county-level.
- A stepwise methodological procedure is conducted using satellite imagery of nighttime lights.
- We find a high degree of county-level clustering in the distribution of emissions per capita.
- High-emission counties tend to be surrounded by counties with relatively low per capita GDP levels.
- We stress the need for consideration of other factors in determining emission patterns.

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ABSTRACT

As the world's largest developing country and greenhouse gas emitter, China's residential energy consumption (REC) is now responsible for over 11% of the country's total energy consumption. In this paper, we present a novel method that utilizes spatially distributed information from the Defense Meteorological Satellite Program's Operational Linescan System (DMSP–OLS) and human activity index (HAI) to test the hypothesis that counties with similar carbon dioxide emissions from REC are more spatially clustered than would be expected by chance. Our results revealed a high degree of county-level clustering in the distribution of emissions per capita. However, further analysis showed that high-emission counties tended to be surrounded by counties with relatively low per capita GDP levels. Therefore, our results contrasted with other evidence that REC emissions were closely related to GDP levels. Accordingly, we stress the need for the consideration of other factors in determining emission patterns, such as residential consumption patterns (e.g., consumer choices, behavior, knowledge, and information diffusion).

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) has reported that global surface temperatures have increased by 0.74 ± 0.18 °C (1.33 ± 0.32 °F) during the 20th century. This is likely the result of increasing concentrations of greenhouse gases (GHGs) [1]. Although human activities, including the burning of fossil fuels and deforestation, were only responsible for 3% of carbon dioxide (CO_2) emissions worldwide in the 1990s, the increase in emissions was large enough to exceed the absorptive capacity of natural processes (e.g., photosynthesis). Energy use for power generation in the industrial [2,3], residential [4,5] and transportation sectors [6,7] has been the largest contributor of GHG emissions. In particular, approximately 10–35% of national energy consumption was from the residential sector worldwide in the late 1990s and 2000s [8], and this figure will likely increase as the average person's income, standard of living, and associated access to home appliances, housing and personal transportation increase. Accordingly, great attention has recently been placed on the residential sector's role in generating GHGs [9].

In China, the residential sector is now the second greatest energy consumer behind the industrial sector; total energy consumption in the residential sector grew by 8.43% since 2008 compared to an average increase of 2.58%. The increase in energy consumption by this sector has been driven by three major factors. First, the Chinese government has refocused its economy towards domestic consumption, resulting in a household consumption

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expenditure that was 38.2% of the Gross Domestic Product (GDP) [10]. If the goal of shifting the Chinese economy towards consumption-led growth in the 11th Five Year Plan is met, it is very probable that residential energy consumption (REC) will continue to rise in the future [11]. Secondly, the lifestyles and consumer preferences of Chinese residents have changed as the country continues to develop, with greater individual access to high quality food, comfortable living environments, health care, personal hygiene products and higher education. Finally, the annual per capita energy consumption of urban Chinese residents is 3.5 times that of rural residents, and, with the urban population expected to grow by 20 million per year, the rapid growth of REC is likely to continue.

Given recent increases in REC, estimating associated CO_2 emissions from this source in a spatially explicit manner is critical for combating processes like global climate change. Estimating emissions from REC is usually dependent on statistical data [12], making it difficult to produce a spatially realistic representation of emissions. However, because artificial lighting is a unique indicator of residential activity, datasets derived from satellite imagery of nighttime lights have been used to map phenomena which would otherwise be difficult to map through ground surveys. There have been many studies examining the use of these datasets for determining spatiotemporal dimensions of socio-economic factors, including GDP, urban sprawl, impervious surfaces, and ex-urban development. More recently, these datasets of nighttime lights have been used as proxies for estimating CO_2 emissions. The first global map of CO_2 emissions had a spatial resolution of 1 degree and was developed by combining the lighted area of a city (using imagery of nighttime lights acquired between October 1994 and March 1995) with country-level ancillary statistical information [13]. Oda and Maksyutov [14] created a high resolution global inventory of annual CO_2 emissions for the years 1980–2007 by combining a worldwide point source database with satellite observations of global nighttime lights distribution. Finally, Ghosh et al. [15] developed a method of mapping spatially distributed CO_2 emissions from the burning of fossil fuels (excluding electric power utilities) at 30 arc-seconds (approximately 1 km^2 resolution) using regression models of nighttime lights images.

In this paper, we present a new approach that uses the human activities index (HAI) as auxiliary data to correct saturated nighttime lights and to fill values in areas lacking nighttime lights. Using our methodology, satellite images of nighttime lights may serve as a useful proxy for the distribution of CO_2 emissions from REC. Finally we used the emissions distribution to test the hypothesis that counties with similar CO_2 emissions from REC are more spatially clustered than would be expected by chance.

2. Data and methodology

We used images of nighttime lights collected by the U.S. Air Force Defense Meteorological Satellite Program's (DMSP) Operational Linescan System (OLS), which has been cited as a remarkable example of a global earth observing satellite sensor for detecting human activity [16]. This low orbiting satellite uses the visible/near infrared waveband (0.4–1.1 μm) for detecting lights and the thermal infrared (10.5–12.6 μm) band to filter cloud cover [17]. The satellite typically makes passes a study area between 8:30 p.m. and 9:30 p.m. local time, and annual global composites of temporally stable nighttime lights have been produced by the National Geophysical Data Center (NGDC) covering the period from 1992 to 2008 [18]. There are three versions of the data available for download, including (1) "raw," (2) "stable lights", and (3) "calibrated" versions [19]. We used the stable lights product (spatial resolution: 1 km^2), which removes clouds, gas flares, lightning, and other ephemeral and extraneous signals using the procedure described by Elvidge et al. [20]. Images used captured nighttime lights over mainland China for the year 2000. Using these images, we conducted a new stepwise methodological procedure (Fig. 1) to map CO_2 emissions from REC.

2.1. Calculation of CO_2 emissions from REC

To calculate CO_2 emissions from REC, we used residential energy matrix tables for 12 fuel types from China's Energy Statistical Yearbook for the year 2000 [21] to estimate CO_2 emissions in that year in rural and urban areas separately. Following IPCC guidelines [22], we used the following equation to calculate CO_2 emissions from REC:

$$E_{CO_2} = \sum_j A_j * ALC_j * C_j * O_j * 44/12 \quad (1)$$

where E_{CO_2} is the total CO_2 emissions from energy consumption (tons), A_j is the amount of fuel consumption j (tons or cu m (cubic meter) for gas), ALC_j is the average low calorific value of fuel j (kJ/kg or kJ/cu m), C_j is the carbon emission factor of fuel j (kg C/GJ), and O_j is the carbon oxidation rate of fuel j. The average low calorific values, carbon emission factors, and carbon oxidation rates for each fuel j are listed in Table 1. The coefficient of emission conversion from heat, a secondary energy source, was also used in our study.

2.2. Threshold method

We identified urban and rural areas based on nighttime light coverage for further construction of the HAI regression model. Satellite imagery has been widely used to map urban sprawl, although confusion exists around the use of empirical thresholds to delineate city boundaries. Imhoff et al. [23] has suggested that a threshold of 89% could remove ephemeral light sources and the "blooming" of light onto water bodies adjacent to cities while still leaving the dense urban core intact. However, Small et al. [24] has argued that a single threshold for all cities could result in an

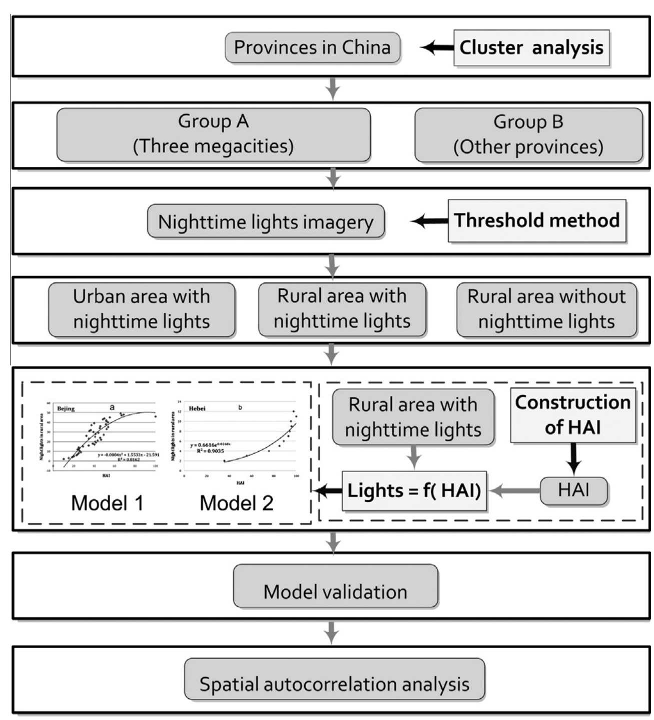

Fig. 1. Methodological framework used in this study.