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Evaluation of energy-related household carbon footprints in metropolitan areas of Japan

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ABSTRACT

In the Post-Paris Era, urban emissions have received worldwide attention as cities are considered to be responsible for most of the world's environmental footprint. A better understanding of urban CO_2 emissions and their related carbon footprints offers benefits to policymakers interested in promoting effective and efficient low-carbon solutions. In particular, a clear determination of direct and indirect emissions inventories (that is, identification of emissions related to specific sources) can provide a valuable baseline for the planning, assessing, implementing, and monitoring of urban mitigation actions. Focusing on the Japanese urban residential sector, this paper uses an established urban database and emission database based on global-related input-output analysis to systematically analyze household carbon footprints related to energy demand, targeting both direct and indirect energy-related CO_2 emissions in Japan's megacities. The results reveal the city-specific emissions status of Japan's three major metropolitan areas, showing, for example, that Tokyo is a source of high direct emissions, while Utsunomiya is a significant source of indirect emissions. The study also tentatively concludes that the depopulation of cities can result in higher per capital emissions, both direct and indirect, as they relate to energy demand. Improved sector and spatially explicit information for better mitigation policymaking and environmental education at the urban level is presented. Valuable insights are offered through an in-depth investigation of the relationship between CO_2 emissions and urban socioeconomic activities, benefitting future low-carbon city research and practice.

1. Introduction

In the Post-Paris Era, increasing attention is being given to global CO_2 emissions mitigation, with particular focus on the world's cities (Fujii et al., 2016; Togawa et al., 2014). This urban focus comes as no surprise since cities are considered responsible for a majority of anthropogenic CO_2 emissions (Cooper, 2016; Van de Graaf, 2017). A better understanding of emissions sources and drivers and the design and impact of countermeasures is necessary to support ongoing efforts to reduce these CO_2 emissions (Dong et al., 2016b; Kok et al., 2006). Cities are the carriers of the intensive socioeconomic metabolism of human beings as well as being responsible for most of the world's environmental footprint (Dong et al., 2016a,b). With the growth of urban populations over the past several decades, cities now accommodate more than half of the world's population and have become a critical sector in energy consumption and energy-demand emissions. As a consequence, urban CO_2 emissions have emerged as an extremely important consideration in any comprehensive policy aimed at reducing the harmful effects of anthropogenic emissions (Liang et al., 2016a,b, 2014; Sun et al., 2017). Among the various urban sectors, the household sector is critical; it accounts for roughly 70% of final consumption expenditures, an amount that is expected to increase given the continuing urbanization process and the projected rise in living standards (Kennedy et al., 2009). Urban household emissions and inventories are thus attracting increased attention (Li et al., 2015; Nässén, 2014; Pukšec et al., 2014; Su et al., 2017) and are expected to play a major role on the consumer side of CO_2 reduction polices.

That urban CO_2 emissions need to be a crucial part of any mitigation policy discussion is undeniable. However, compared to the number of studies done on global CO_2 emissions at the national level (Andrew et al., 2009; Jones and Kammen, 2011; Wiedmann, 2009b) or the regional level (Brizga et al., 2017; Liang et al., 2007; Tian et al., 2014, 2016), there are still relatively few urban-scale studies. The need for such studies seems clear, particularly those focused on individual city CO_2 emissions and current intercity disparities (Feng et al., 2014; VandeWeghe and Kennedy, 2007).

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A systematic analysis of urban CO_2 emissions and mitigation focused on the household sector offers a solid basis for the design of countermeasures to improve consumption patterns and alleviate some of the more serious negative impacts of climate change (IPCC, 2014b). Since urban residential CO_2 emissions are a critical consideration in any comprehensive CO_2 mitigation policy, identifying urban household patterns of consumption is essential (Chen et al., 2017; Geng et al., 2017; Park et al., 2017). Urban policymakers clearly need to confront the coming challenge and guide urban residents to cultivate an economical and environmentally friendly lifestyle. However, without a sufficient understanding of city-scale emissions and intercity differences, effective mitigation policies will be all but impossible to devise and implement (Wakiyama and Kuramochi, 2017; Zang et al., 2017). Household CO_2 emissions can be assigned to either monetary or physical consumption categories and can be sourced from various sectors, e.g., accommodation, transportation, and energy. Among these, the household energy-related sector stands alone in causing CO_2 emissions both directly and indirectly (Jiang, 2016; Setlhaolo and Xia, 2016). For example, the direct consumption of energy, e.g., petrol, gas, water, and kerosene, creates CO_2 directly. In contrast, carbon emissions embedded in demand-responsive energy production processes are treated as indirect emissions. Indirect household emissions have been the focus of a number of input-output (IO) models. It has been demonstrated, for example, that more than 60% of household emissions are produced in an indirect way in the Korean residential sector (Park and Heo, 2007). In fact, indirect energy consumption (energy consumption embedded in the production process) and its associated carbon emissions have been found to be greater than direct consumption and emissions in a number of urban household studies (Feng et al., 2011), pointing to the need to include both components when measuring total household contributions (Sommer and Kratena, 2017; Veeramani et al., 2017). In addressing this issue, measuring carbon footprints offers a scientific approach to comprehensively assessing carbon emissions associated with human activity (Kanemoto et al., 2016; Wiedmann, 2009a). This approach is used in the present study to capture the full environmental burden that can be linked to the urban residential sector.

Japan continues to make significant efforts to promote low-carbon policies (Fujii et al., 2016; Togawa et al., 2014). As such, it offers an ideal laboratory to conduct studies to address the research challenges noted above and to test the feasibility of potential mitigation methods. Furthermore, Japan has a large integrated and detailed statistical database and spatial data at the urban and regional levels that strongly support regional decision-making regarding low-carbon actions (Togawa et al., 2016). In addition, as a mature, developed country, Japan's CO_2 emissions from its residential sector account for a major portion of the country's overall emissions. Of the total Japanese national CO_2 emissions in 2014, estimated to be 126.5 million tons, 19.2 million tons were associated with the residential sector (compared to 42.6 million tons from the transportation sector, 21.7 million tons from the industrial sector, and 26.1 million tons from the commercial sector). Moreover, while emissions from the industrial sector have been decreasing in recent years, emissions from the residential sector increased 6.6% between 2005 and 2014 (MOE, 2016). Additionally, since the "Great East Earthquake" in 2011 put tremendous pressure on the energy supply and carbon mitigation countermeasures, reducing residential CO_2 emissions has become a critical topic. Taken together, these factors make Japan an ideal testing laboratory and a promising source of enlightening insights into the future of other regions in the world.

Given the above argument, the following questions merit consideration in order to better understand urban household emissions in Japan: (1) What are the trends for household energy-demand consumption and emissions in Japanese megacities? (2) Differences between emissions from direct combustion and emissions embedded in related indirect processes? (3) What are the relevant emissions patterns and what are the underlying factors, e.g., per capita emissions, urban population density, and consumption style? (4) Are there differences in household energy consumption among the various metropolitan areas (spatial features)? Answering these questions has important policy implications for the design and implementation of effective local and regional measures.

To provide answers, the present study investigated household energy-demand carbon footprints, including energy-demand CO_2 emissions generated both directly and indirectly, using an advanced IO approach and a detailed local database along with relevant statistics. We first calculate direct household emissions using the Family Income and Expenditure Survey (FIES) together with CO_2 emission intensities derived from the Resource Energy Statistics of Japan. We then evaluate indirect residential household CO_2 emission based on emission intensities derived from 3EID (Embodied Energy and Emission Intensity Data for Japan Using Input-Output Tables) and the household consumption inventories in three metropolitan areas in Japan: the Kinki, Chukyo, and Shuto areas. The source categories, including household-related features of carbon footprints and intercity disparities, are investigated in depth and provide detailed information for future mitigation policy and priority-setting. Importantly, the present study presents sectoral and spatially explicit information that will enable more effective mitigation policymaking and environmental education at the urban level.

The remainder of the paper is organized as follows: Section 2 presents the methodology to evaluate household CO_2 emissions in both direct and indirect ways; Section 3 describes the case study areas; Section 4 presents analytical results and related discussions; Section 5 summarizes conclusions and outlines policy implications.

2. Methods and data

2.1. Household CO_2 emissions on energy demand

Household energy consumption can be classified as either direct consumption, which involves the combustion process, or indirect consumption, which involves other processes such as energy production and disposal. As a general rule, the production of goods and services requires the direct use of inputs, which, in turn, use inputs from other sectors at different stages of the industrial process; this latter component is called indirect use (Liu et al., 2011). In this study, we focus on the unique household need that generates emissions not only directly but also indirectly, the household need for energy. We compare the two emissions types and identify intercity disparities. For purposes of the study, energy directly consumed by a household consists of manufactured and piped gas, liquefied propane, kerosene, and gasoline used in combustion. When a household consumes (combusts) one or more of these energy sources, direct emissions are generated. At the same time, households also consume energy in other ways, using, for example, electricity, natural gas, water, and other fuels for lighting and heating. Although direct utilization of these energy sources does not generate CO_2 emissions directly, their upstream production can be a source of substantial emissions.

It seems clear that when we focus on emissions associated with the energy-related consumption of the residential sector, both direct and indirect emissions should be included. Water is an especially interesting case. Although most residential energy-demand emissions occur both in the production and utilization processes, water usage, which includes sewage, generates emissions during the final disposal process. Therefore, we considered the waste water disposal process as part of the water-need emission intensity. Fig. 1 shows the system boundaries of the study.

2.2. Data compliance for evaluating household energy-related CO_2 emissions

As discussed earlier, household CO_2 emissions are embedded in