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Producer cities and consumer cities: Using production- and consumption-based carbon accounts to guide climate action in China, the UK, and the US

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ABSTRACT

Meeting the commitments made in the Paris Agreement on climate change will require different approaches in different countries. However, a common feature in many contexts relates to the continued and sometimes increasing significance of the carbon footprints of urban centres. These footprints consider both production or territorial (i.e. Scope 1 and 2) emissions, and consumption or extra-territorial (i.e. Scope 3) emissions. Although a growing number of cities have adopted targets for their production-based emissions, very few have even started to analyse or address their consumption-based emissions. This presents a potential challenge for urban policymaking if consumption emissions rise while production emissions fall, and for climate mitigation more broadly if emissions are effectively migrating to areas without carbon reduction targets or capabilities. To explore these issues, in this paper we analyse and compare production- and consumption-based emissions accounts for urban centres in China, the UK and the US. Results show that per-capita income and population density are strong predictors of consumption-based emissions levels, and consumption-based emissions appear to diminish but not decouple with higher per-capita incomes. In addition, results show that per-capita income is a predictor of net emissions - or the difference between production- and consumption-based accounts - suggesting that continuing increases in per capita income levels may drive the 'leakage' of urban emissions. These findings highlight a risk in placing too much faith in city-level climate strategies focused only on production-based emissions, and stress the importance of new city-level initiatives that focus on consumption-based emissions, especially in cities that are shifting from producer to consumer city status.

1. Introduction

Territorial greenhouse gas (GHG) emissions — also known as Scope 1 and 2 emissions - have declined across a large number of Western countries (see for example Peters et al., 2011a,b; Peters and Hertwich, 2008; Fischer, 2011). However, these reductions have often been more than off-set by increases in extra-territorial or consumption-based emissions, and a number of analyses suggest this trend will continue (Davis and Caldeira, 2010; Peters et al., 2011a,b).

In this context, much academic debate has centred around the importance of consumption-based carbon accounting (Steininger et al., 2014). Production-based accounts, which are currently the basis for all widely accepted carbon management frameworks, assign responsibility for emissions at the point where they are produced. In contrast, consumption-based accounts assign responsibility for emissions to the end of the supply chain where goods and services are ultimately consumed.

In this paper, urban areas that out-source more emissions than they in-source are referred to as 'consumer urban areas', and to those that in-source more than they out-source are referred to as 'producer urban areas'. For consumer urban areas, consumption-based carbon accounts will exceed production-based accounts as

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they take account of the extra emissions that are driven by their consumption but that do not feature in their production-based accounts. For producer urban areas, the opposite will be true.

Employing consumption-based, rather than production-based, accounting methods can have significant advantages (Afionis et al., 2017). By addressing emissions at the point where goods and services are consumed, consumption-based accounting ensures that all sources of emissions associated with a good or service are considered regardless of the place where they were produced. Such approaches preserve the principal of common but differentiated responsibility, a cornerstone of international climate negotiations (Gupta, 2010), by connecting responsibility for emissions to the volume of consumption. Research also suggests that consumption-based emissions are more closely connected with measures of well-being than production emissions and may therefore be more appropriate for guiding policymaking (Steinberger et al., 2012).

Consumption-based accounting approaches at the urban level may be of particular importance. Urban areas are home to more than half the world's population, are responsible for 67–76% of energy use and 71–76% of carbon emissions, and are frequently the final destination for the consumption of goods and services produced along globalised supply chains (Grubler et al., 2012; Seto et al., 2014). In addition, urban governments often have unique influence over local planning decisions, building stocks, transport networks and other infrastructure, and close connections with local civic groups, businesses, and regional governments, making them well positioned to develop innovative and ambitious actions to address climate change (Sullivan et al., 2013; Bassett and Shandas, 2010). In reflection of their importance, networks of urban areas coordinating action and sharing best practices have flourished and urban areas and other non-state actors were recognized as one of four 'key pillars' of action in the UNFCCC Paris Agreement on climate change (Chan et al., 2015; Anguelovski and Carmin, 2011).

Owing to data limitations, the technical complexity of the analysis, and the relatively new nature of the field, relatively few analyses have looked at consumption-based carbon accounts in urban areas. Existing research has suggested that consumption-based accounts are larger than production-based accounts in some urban areas. Looking at China, Feng et al. (2014) found that 70% of emissions from goods and services consumed in Beijing, Shanghai and Tianjin, three of the largest urban areas in China, occurred outside city boundaries. In the UK, Minx et al. (2013) found that approximately 90% of urban areas are net importers of embedded CO_2 emissions. Other research has explored relationships between consumption emissions and household size (Heinonen et al., 2013), levels of wealth (Wiedmann et al., 2015), and urban and rural areas (Feng et al., 2014).

To our knowledge, no analysis has been published that includes urban areas from multiple countries and that considers both production- and consumption-based accounts. This paper seeks to contribute to the conversation around climate action in urban areas by comparing production- and consumption-based emissions for 13 urban areas in China, 15 urban areas in the UK and 17 urban areas in the US. In so doing, this analysis explores insights that can be drawn from production- and consumption-based accounts across a range of urban areas with different population sizes, levels of wealth and levels of density. The paper is structured as follows: In Section 2 the methodology is described, in Section 3 the findings of the analysis are presented, in Section 4 a discussion policy implication are discussed, and in Section 5 conclusions are offered.

2. Data and methodology

Comparative analysis of consumption and production based accounting approaches across international urban areas, the intent of this paper, has been constrained in the past by widespread lack of data on urban consumption emissions. Recent work, however, has provided an opportunity in three countries. In China, consumption accounts for 13 urban areas can be derived from input-output tables produced from regional statistical agencies. These data have previously been presented in Mi et al. (2016) and can be paired with urban production emissions estimates developed by Shan et al. (2016). In the US, per capita consumption emissions for urban areas can be aggregated from Jones and Kammen (2011). While this data could be used to provide estimates for a large number of US urban areas, the availability of production based estimates limited analysis to 17. Finally, using data and statistical methods developed by Minx et al. (2013) and Millward-Hopkins et al. (2017), consumption accounts were developed for 13 urban areas in the UK and matched with production emissions data from the UK government.

2.1. Chinese urban areas

This paper draws on data and methods developed by Shan et al. (2016), whose analysis is based on the IPCC territorial emissions accounting approach (IPCC, 2006; Mi et al., 2016). Each inventory covers 47 socioeconomic sectors, 20 energy types and 9 primary industry products.

Consumption-based accounts for Chinese urban areas are drawn from analysis previously undertaken by Mi et al. (2016). Within this analysis, final demand is comprised of expenditure from rural households, urban households, government expenditure, fixed capital formation and changes in inventories, across 42 sectors. These data were supplemented with population data and municipal expenditure data compiled by the National Bureau of Statistics (NBSC, 2015) and data on density is drawn from Cox (2012).

2.2. US urban areas

Production-based emissions estimates for US urban areas were drawn from a number of sources, including studies commissioned by municipalities, research by C40 Cities, academic publications, and research from the US Environmental Protection Agency. Each of these sources describes their work as following standardised IPCC approaches.

Data on consumption-based footprints was obtained from the Renewable and Appropriate Energy Laboratory at University of California in Berkeley, where a combined Environmental Input-Output Life Cycle Analysis approach was taken to estimate emissions. This model allowed for the quantification of carbon footprints of U.S. households for different sizes and income brackets, including emissions embedded in transportation, household energy, food, goods, and services code (Jones and Kammen, 2011). Data was aggregated by postal code, then converted into a per capita average using data on average household size and population by postal.

2.3. UK urban areas

Production-based emissions for UK local authorities are available open source from the Department of Energy and Climate Change (DECC, 2015) These data disaggregate emissions into domestic, industrial and commercial, and transport sectors, and are available in both per capita and aggregate terms.

The methodology described in Millward-Hopkins et al. (2017) was employed to develop consumption-based carbon footprint estimates. Final demand is comprised of government spending, capital investment, non-profit institutes serving households

(NPISH) spending, and household expenditure across 292 sectors: 110 in the UK, and 26 in each of 7 global regions. In order to calculate household spending, national-level spending profiles for persons of different economic status (employed, student, retired, self-employed, etc.), are combined with the number of residents in each city falling into each profile. Total city-level household expenditure is then adjusted to reflect local incomes using the ratio of the median income measured at the city-level to that at the national-level. The 3 other sources of final demand are obtained via the methodology of Minx et al. (2013), which assumes that national-level demand can be distributed across the population on an equal per-capita basis.

In order to calculate the emissions intensity of expenditure, the EE-MRIOA tables developed by Barrett et al. (2013) for the UK Government's Committee of Climate Change (2013) are utilised. These tables show the emissions per unit of expenditure (both direct and along supply chains) for 292 sectors. Following Minx et al. (2013), it is assumed that national-level carbon intensities are relatively constant across the UK and are therefore applicable in each urban area. These tables do not account for direct household emissions, and hence these are added separately from the DECC local authority-level, production-based accounts that were introduced in section 2.1. Data on urban GVA and population for urban areas in the UK is drawn from the Office of National Statistics Website.

Although analysis could have been extended to all local authorities in the UK, analysis was restricted in order to provide a sample that could be compared with data from the US and China. The urban areas chosen for the UK are the 9 'core' urban areas, which are the 9 largest urban areas in the UK by economic output, plus an additional 6 urban areas that were chosen based on relatively high/low employment rates and average incomes in order to represent a range of city types found across the UK.

2.4. Limitations

A number of limitations are of note. First, the number of urban areas analysed is relatively small and for one year for each city. Second, there is reason to believe that the urban areas for which data on both production and consumption accounts are available are not necessarily an unbiased sample. In both China and the US our data seems to bias towards larger and wealthier urban areas, and in the US urban areas which have commissioned climate studies are more likely to have taken climate action. Third, the years of data do not match across datasets. For the UK and China, data for consumption and production emissions are for the year 2007. For the US, consumption estimates are for the year 2005 (Jones and Kammen, 2011), while production estimates are for years between 2005 and 2010. Finally, no 3 stage IO analysis, which would allow for impacts at the city, national and international level to be distinguished, was undertaken. A few recent studies in China (Meng et al., 2016, 2017; Shao et al., 2016) have used a 3 stage IO analysis. Meng et al. calculated energy-related PM emissions for Beijing which considered emissions produced within Beijing for consumption in Beijing, emissions produced in the rest of China for consumption in Beijing and emissions produced outside china for consumption in Beijing. We are not aware similar sub-national input-output data exists for other urban areas worldwide and therefore distinguish only the emissions intensities of products within and outside the country where the city resides. The domestic component within a country therefore differs by the level and pattern of spending and not the emissions intensity of domestic production.

3. Results

3.1. Comparing production- and consumption-based accounts

Production- and consumption-based accounts represent complementary approaches to understanding a city's contribution to climate change. In the following section, these accounts are compared to understand how these perspectives differ between countries when key urban characteristics are taken into consideration.

Fig. 1 shows production- and consumption-based emissions (per capita) for urban areas in China, the US and the UK. Below the line, per capita emissions from production are greater than from consumption, indicating a net flow of embodied emissions out of the city. Above the line the reverse is true. Urban areas above the line are thus "consumer cities" while urban areas below the line are "producer cities". Several points are worth noting.

First, consumption-based emissions are generally higher than production-based emissions in urban areas in the UK and US, while production emissions are generally higher than consumption emissions in Chinese urban areas. Exceptions to this general finding are Beijing and Shanghai, where consumption emissions are comparable or higher than in UK urban areas, and Houston in the US, where production emissions are greater than consumption emissions.

Second, the range of emissions, both from production and consumption standpoints, is significantly greater in Chinese and US urban areas than in UK urban areas. With respect to consumption emissions, the highest and lowest UK urban areas vary by 3.6 tonnes CO2e per capita while in Chinese urban areas the highest and lowest vary by nearly 12 tonnes CO2e per capita and in the US the difference is 10.9 tonnes CO2e per capita. With respect to production emissions, the highest and lowest UK urban areas vary by only 1.9 tonnes per capita, while Chinese urban areas vary by more than 10 tonnes CO2e per capita and in US the highest and lowest US urban areas vary by 11.9 tonnes CO2e per capita.

Third, only one Western city – Houston – lies below the solid line and is therefore a producer city, while all other Western urban areas are above the line and are therefore identified as consumer urban areas. By contrast, five of the thirteen Chinese urban areas categorised are producer urban areas, but for two of these urban areas, Shenyang and Harbin, the difference between production and consumption emissions is less than one tonne per capita. Only a small minority of urban areas in this dataset are therefore significant exporters of emissions (on a per capita basis). As will be discussed further below, emissions from these producer urban areas are dominated by specific point source emissions from industrial sources. Houston, for example, has a large oil refining and petrochemicals industry, and Tangshan is a centre for the production of petroleum products, machinery and steel refining.

3.2. Income levels and urban emissions

The following section explores relationships between urban income and emissions. Although these findings are not causative, the relationships found add to our understanding of urban areas' contribution to climate change at different levels of economic development.

Fig. 2 shows the relationships between urban income per capita in the China, the US, and UK, and per capita production emissions. Two findings are evident. First, across urban areas, approximately 1/3 of the variation in per capita production emissions can be explained for by income, suggesting a relationship between income and emissions, or between both of these factors and/or with additional variable(s). Second, there are different patterns to be

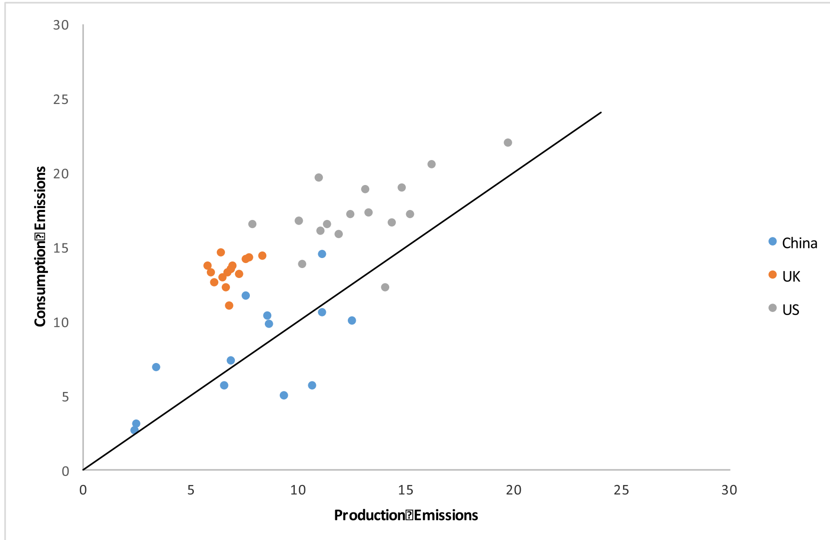

Fig. 1. Production- and consumption-based emissions per capita for cities in China, the US and UK. Above the solid line cities consumption-based emissions are greater than their production-based emissions. Below the line the opposite is true.

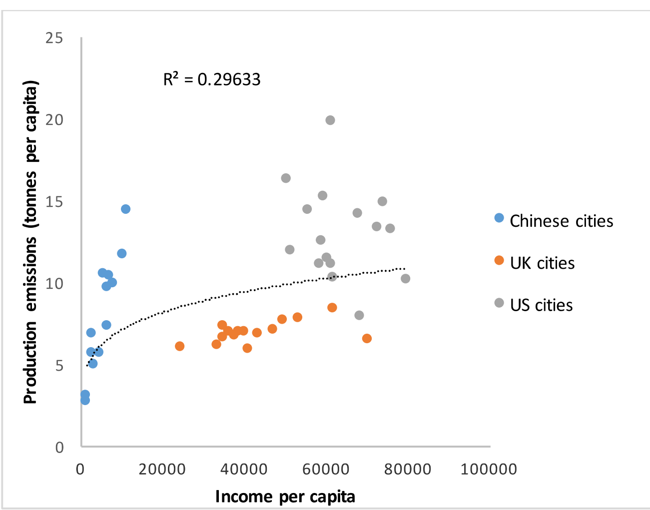

Fig. 2. Production-based emissions versus average per capita income.

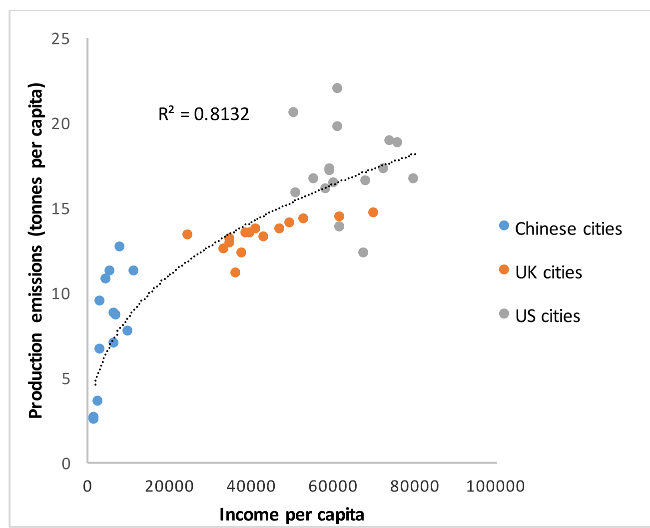

Fig. 3. Consumption-based emissions versus average per capita income.

observed between urban areas in China, and urban areas in the UK and US. Focusing only on Chinese urban areas, higher income appears to lead to higher production emissions, likely as a result of increases in private transport and people engaging in other high emitting activities for the first time. Among US and UK urban areas, the differences are relatively small and it is not clear higher incomes necessarily increase emissions.

Fig. 3 shows a much strong relationship between per capita income and per capita consumption-based emissions. Fitted with a log-linear relationship (to account for the largest differences in income between urban areas), the urban areas show a positive but diminishing correlation between income and consumption-based emissions wherein more than 80% of the variation in emissions is explained by differences in income. This finding is suggestive that changes in lifestyles and consumption habits at relatively lower income levels (less than approximately 40000 USD per capita) have significant impacts on emissions, while at higher income levels (greater than approximately 40000 USD per capita), the impact of changes in lifestyles and consumption habits from higher income is progressively smaller.

In the Chinese urban areas in this analysis, production- and consumption-based emissions both rise with income, suggesting two possible (non-exclusive) explanations: rising demand for emissions intensive goods and services being met by local production, or rising demand for goods and services being met by imports of goods and services which are approximately equal in scale to the embodied emissions of newly developed exports. In the US and UK urban areas, production-based emissions do not change significantly with income, suggesting that rising demand for goods and services with income is met by net imports of goods and services.

Fig. 3 shows net consumption, the difference between per capita consumption-based emissions and per capita production-based emissions. While the correlation in Fig. 4 is not as strong as in Fig. 3, an interesting new dimension is added: income not only correlates with higher consumption emissions (Fig. 3) but also with the difference between consumption and production emissions.

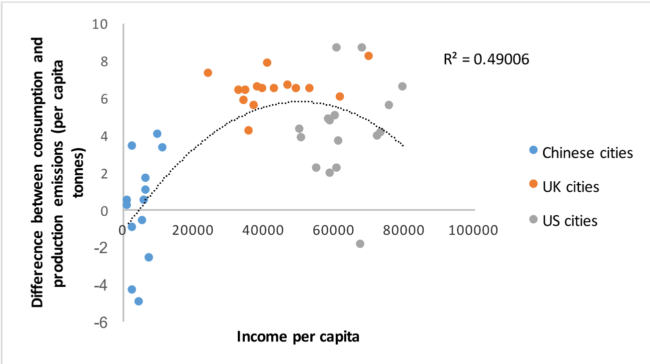

Fig. 4. Net emissions (consumption-based emissions - production-based emissions) versus average per capita income.

This finding suggests that rising incomes not only lead to rising demand for goods and services, but that demand is met by imports, rather than local production. This provides evidence for weak leakage across this sample of urban areas, the phenomenon of higher incomes in one location driving the emissions higher in another location.

This figure also illustrates the scale of imported emissions into urban areas. Among Chinese urban areas, net imported emissions are only 0.1 tonnes per capita on average, ranging from −5.0 tonnes per capita in Tangshan to approximately 4 tonnes per capita in Beijing. In the US, an average of 4.1 tonnes per capita on average are imported into urban areas with a range of −1.7 in Houston to 9.9 tonnes per capita in San Diego. In the UK, the average city imports 6.4 tonnes per capita, ranging from 4.2 tonnes per capita in Newcastle to 8.1 tonnes per capita in London. Within this sample, net emissions are therefore, on average, near negligible for Chinese urban areas. By contrast, average net emissions imports are equal to approximately 1/3 (32%) of production-based emissions in US urban areas and are nearly the same in magnitude as production-based emissions in urban areas in UK (91%).

3.3. Density and urban emissions

To complement the analysis of income as a key urban characteristic, the following analysis explores relationships between density and production and consumption accounts. In so doing, this analysis raises questions about effects that urban planning may have on the development of emissions in urban areas.

Fig. 5 plots the level of per capita production-based emissions in each city against the density of each urban area. Two key findings are important to note. First, results show a negative correlation: Lower levels of density are associated with higher emissions levels with approximately two-thirds of the variation in production emissions explained by levels of density. While this result is not causative, it suggests that urban planning decisions may shape economic activities and consumption patterns which in turn drive energy use and emissions. However, it is important to note that a process moving in the opposite direction could also be present – existing economic activities and consumption patterns may influence planning decisions, energy use and emissions.

Second, a high level of variation is present across Chinese urban areas, ranging from 11700 people per km^2 in Hengshui to 3300 in Ningbo. In the US and UK, by contrast, the level of variation between urban areas is much smaller. In the US, the most-dense urban area, Los Angeles, has 2400 people per km^2 while the least dense, Minneapolis, has 1000 people per km^2. In the UK, the most-dense urban area, London, has 5600 people per km^2, while the least dense, Hull, has a density of 3800 people per km^2. Whether these differences reflect the historical, cultural or economic makeup of these urban areas, or other influences, is beyond the scope of this paper.

Fig. 6 plots urban consumption-based emissions per capita against urban population density. Results show that a negative correlation exists between the level of population density and the level of consumption emissions: as density increases, the level of consumption-based emissions per capita decreases and levels of density explain approximately 75% of the variation in emissions. Coupled with the finding from Fig. 5, this suggests that energy use declines with density, a finding well established in the literature. However, it is not clear from these figures if any relationship exists between net emissions (the difference between production- and consumption-based emissions) and density.

In order assess whether density can be connected with the net change in imports/exports of embedded emissions – emissions released during the production and transport of a good or service to a consumer (Peters et al., 2011a,b)- Fig. 7 plots net imports of emissions against density. Results show only a weak relationship between net emissions and density which appears to be driven by a small number of Chinese urban areas. Considering Figs. 5 and 6, it would appear that density is associated with lower production- and consumption-based emissions, but has no clear impact on the source of those emissions.

3.4. Testing for statistical significance

In order to test the statistical significance of these findings, we

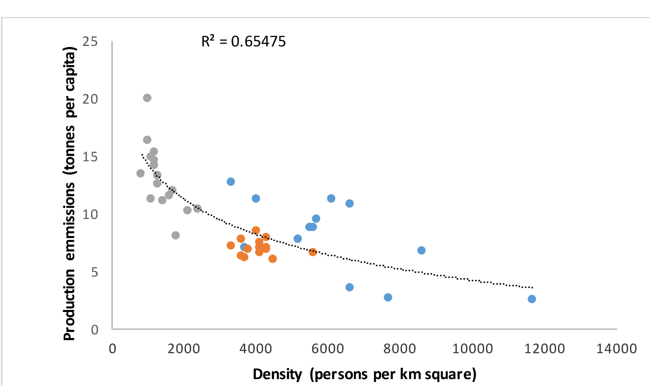

Fig. 5. Production-based emissions per capita vs persons per square kilometre.

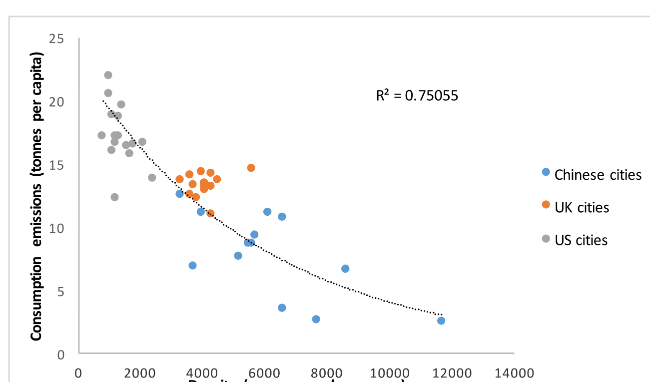

Fig. 6. Consumption-based emissions vs persons per square kilometre.

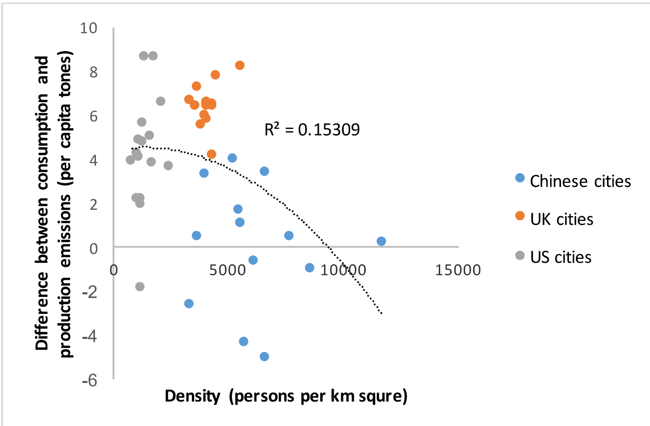

Fig. 7. Net emissions per capita (consumption-based minus production-based emissions) versus persons per square kilometre.

calculate Kendall's Tau, a measure of parametric statistical dependence, across four variables where correlations were found: Density, consumption emissions per capita, production emissions per capita, and income. Supporting the figures above, the strongest measures of statistical dependence are between consumption accounts and income, followed by relationships between density and both production and consumption emissions. Outputs are shown in Table 1 with all results with statistical significance $p < 0.01$ shown with a star (*) and results with a significance level greater than 0.05 omitted.

4. Discussion

4.1. Implications for urban climate action

While nation states continue to make important commitments to global climate action, urban areas can provide leadership, and take many of the actions needed to fulfil those commitments. Our analysis underlines the importance of urban areas as key actors in the fight against climate change, but raises questions about the approach to climate action being taken.

The first of these questions pertains to the way we understand and approach urban emissions. The extent that urban activities and metrics can be linked with emissions informs the extent that these activities and metrics can be used to inform policymaking. For example, the connection between density and emissions emphasises a potential benefit of compact, connected and coordinated communities.

While production-based accounting approaches are widely employed in urban areas (through the Global Protocol for Cities), consumption-based accounts are rarely applied, even though our analysis shows that they are more closely connected with two key urban metrics. In the sample of urban areas in this analysis, more than three-quarters of the variation in consumption-based emissions can be explained by income, while less than one-third of the variation in production emissions can be explained by income. With respect to density, approximately two-thirds of the variation in production-based emissions can be explained by income while three-quarters of the variation in consumption-based emissions can be explained by income. A consumption-based approach to urban emissions therefore highlights the importance of income and density, and raises the concern that these metrics are receiving relatively less attention than they merit in informing urban actions.

Secondly, analysis illustrates that urban characteristics, much more than the country in which urban area is located, describe the structure of urban emissions. While urban areas in this analysis tend to cluster by country, urban characteristics are much better predictors of emissions. Although average per capita incomes in London are much higher than those in Shanghai, both are relatively dens, large urban areas where there is a significant gap between production-and consumption-based emissions. While Houston and Ningbo are at different income levels, each is a major port where urban emissions are relatively high due to energy intensive industrial activities. Common opportunities for climate mitigation across urban areas with particular characteristics, including megacities (He et al., 2016), rapidly growing developing and middle-income cities (Colenbrander et al., 2015, 2016), and urban areas with other specific characteristics (Gouldson et al., 2015; Sudmant et al., 2015), have been well established in the literature. However, the extent to which these common characteristics may be crucial indicators of the need for coordination and learning between these urban areas, and for future research, may be underappreciated.

Finally, this analysis raises questions about the way carbon emissions are being addressed in urban areas, and about our understanding of urban areas as actors in the fight against climate change. Much more than may be realised in current discussions, urban areas are emerging as centres of consumption and drivers of emissions across globalised supply chains. Although urban areas such as Shanghai, Beijing and Xian and Dalian are large producers of emissions, to an even greater extent they are centres of demand for emissions intensive goods and services. This is the case even to a greater degree in urban areas such as San Diego and Manchester in the US and the UK. Further, analysis suggests that the growth of consumption emissions in these urban areas may be driven by imports of goods and services, rather than local production.

These questions raise implications for urban climate action. Firstly, although the relationships explored in this analysis are not necessarily causal, a projection of emissions suggests the potential for massive growth in consumption based ‘emissions demand’ from Chinese urban areas, posing a significant challenge to national and global emissions targets. The level of uncertainty surrounding this assertion should be noted. Historically, there has been a strong link between income levels and consumption-based emissions (Hertwich and Peters, 2009), and it has been suggested that consumption-based emissions peak but fail to decline even at high income levels (Aldy, 2006; Knight and Schor, 2014). Recent research in the UK projects falling consumption-based emissions – in contrast with previous research (Scott and Barrett, 2015). However, globally, absolute decoupling of income from consumption-based

Table 1
Kendall's Tau.

	Density	Consumption emissions	Production emissions	Income
Density				
Consumption emissions	−0.6416*			
Production emissions	−0.5370*	0.4598*		
Income	−0.5634*	0.7146*	0.3605*	
Net emissions	–	0.3340*	−0.2061	0.3319*

emissions seems unlikely as long as absolute demand for goods and services continues to grow (Schandl et al., 2015), and historical estimates have tended to underappreciate the potential for economic growth to lead to rising – rather than falling - emissions intensities (Pretis and Roser, 2016). Further, continued urbanisation in China could raise emissions even without economic growth due to rural populations having a lower emissions footprint (Wiedenhofer et al., 2017).

Secondly, rising incomes and rapid urbanisation, especially in developing urban areas, may lead to a gradual concentration of production-based emissions in specific places, potentially reducing the efficacy of production-based mitigation strategies. This phenomenon, known as 'leakage', comes in two forms. Evidence of 'strong leakage', whereby emissions producing activities are moved in response to specific regulations, has been limited (Peters et al., 2011a,b). In contrast, evidence of 'weak leakage', new emissions concentrating where the costs of emitting is relatively lower, has been found at the international level (Peters et al., 2011a,b; Kanemoto et al., 2014). This process can also operate within nations, and indeed may be more important at the intra-national level if urban areas lead climate action. In China the wealthiest urban areas and regions have taken the largest efforts to reduce emissions (Liu, 2015), and Wang et al. (2015) found some evidence for weak leakage at a regional level.

Finally, if urban areas are more important as consumers than producers of emissions, then it is likely that some effective climate actions focus on are consumption-rather than production-based emissions. Shifting from a production-to a consumption-based mitigation strategy can be both politically and technically challenging. In the following section the options urban areas have to address consumption-based emissions are considered.

4.2. Addressing urban consumption-based emissions

Emissions accounts serve as the basis for any climate action program, providing data to understand the sources of emissions and thus begin to assess options for mitigation. Potentially of even greater importance, emissions accounts assign responsibilities: Should the burden of action fall on those who emit greenhouse gases while producing goods and services, or on those who demand and ultimately consume the products and services that are produced? If action against climate change were coordinated at a global level and markets were relatively efficient, the choice of a carbon accounting framework would be less consequential. Based on the elasticities of supply and demand, the burden of action would be shared across producers and consumers. However, in reality, the politics of climate change and the inefficiencies of markets result in significantly different outcomes if climate policy assigns the burden of action to the producers of emissions (through production-based accounts), or the consumers of emissions intensive goods and services (through consumption-based accounts).

Although there has been intense academic debate on these issues (see Peters and Hertwich, 2008), production-rather than consumption-based accounts are standard at an international level. More importantly in this context, production-rather than consumption-based accounts are also being employed to direct climate action at the urban level. In China, 42 'low-carbon' city and province initiatives have been initiated, including emissions targets for major urban areas such as Beijing, Shanghai and Shenzen and a carbon-trading program covering Beijing, Chongqing, Shanghai, Shenzhen and Tainjin has been operating since 2014 (Munnings et al., 2014). In the UK, the Department of Energy and Climate Change (now a part of the Department of Business, Energy and Industrial Strategy) produces annual accounts of Scope 1 and 2 emissions corresponding to each local council, which in turn guide councils' plans to reduce local emissions (CCC, 2016). Internationally, the Covenant of Mayors has received commitments from more than 500 urban areas to reduce Scope 1 and 2 emissions by at least 20% by 2020 against a 2008 baseline (COM, 2016).

The prospect for the wider adoption of consumption-based emissions accounting approaches is sometimes perceived to be limited (Liu, 2015; Jakob et al., 2014). Calculating consumption-based accounts can be technically complex. Further, employing consumption-based measures may be politically challenging as focus would need to be shifted from a large, but specific, set of energy intensive sectors and actions, to a wide and varied range of goods and services across the economy and across borders. Employing consumption-based accounts would also require that many developed governments (at the national, regional, or municipal levels) take ownership of a much larger body of emissions.

In urban areas, some of these challenges are magnified. Policymakers typically have less technical capacity than their counterparts at the regional and national levels. Further, urban policymakers typically have reduced powers over taxation and no powers over the importing and exporting of goods and services, two key areas for the implementation of consumption-based mitigation measures.

At the same time, urban areas are uniquely placed to influence and coordinate a wide set of local actors and to benefit from the co-benefits of climate actions – the additional impacts beyond those to the climate. While the benefits of reduced emissions are generally diffuse, long-term and relatively uncertain, the impacts of both production- and consumption-based mitigation measures on energy bills, public health, mobility and employment (among other impacts), are relatively local, near-term, and certain. Further, most urban areas are only beginning to develop climate action plans. In contrast with national governments, urban areas are therefore not committed to specific actions, nor have they developed specific capacities which favour particular climate policy approaches. Thus an opportunity exists for urban areas to explore innovative solutions.

These could include the introduction of new urban policy initiatives. Previous research has shown that product and resource efficiency standards can significantly impact on embedded emissions (Kagawa et al., 2013; Somanathan et al., 2014). Similarly, resource and energy efficiency standards applied to new buildings and infrastructure could drastically reduce embedded carbon (Miller et al., 2015; Dixit et al., 2012; Barrett and Scott, 2012). Although urban taxation powers are often limited, many urban policymakers are able to add refundable recycling fees to a wide range of goods (Wheeler, 2008; Kahhat et al., 2008), thereby establishing incentives to reduce consumption and the generation of waste.

Urban policymakers could also support initiatives promoting the reuse of goods and services. Supporting the sharing economy in the form of car sharing (Cervero and Tsai, 2004), bike sharing (Geels, 2012), and more recent and innovative ideas such as tool sharing and office sharing, have the potential to influence emissions. Policies to reduce food waste have particular potential – indeed recent analysis has suggested that some urban areas could make equivalent reductions to their carbon footprints either through extensive and expensive production-based initiatives such as retrofitting buildings or upgrading transport systems, or through presumably much less expensive consumption-based initiatives aimed at cutting food waste (Millward-Hopkins et al., 2017).

Further, reductions in final demand – and thus in consumption-based emissions - could also be secured through changes in urban planning. By influencing urban form and function, and by promoting the development of compact urban areas, policymakers could realize long-term savings in emissions by affecting travel patterns and lifestyles, as illustrated by the connections between urban emissions and density (Sovacool and Brown, 2010; Coorey and Lau, 2007; Jones and Kammen, 2011). Urban planners could also promote the development of durable infrastructure which spread the carbon impacts of capital formation over a longer period. Requiring the development of sustainable, adaptable and reusable buildings, transport systems or infrastructure more broadly could significantly reduce consumption-based emissions especially in rapidly developing urban areas.

A crucial aspect of many of the above measure, is that they are likely to impact on both production- and consumption-based accounts. It is likely that to achieve deep levels of decarbonisation – especially those compatible with limiting average global warming levels to 1.5 °C, are likely to demand that urban areas pursue both production- and consumption-based approaches. And it is likely that the most cost and carbon effective measures urban policymakers could take will also include both production- and consumption-based approaches. Such an analysis, however, has not yet been completed and there is an urgent need for research to expand the number of urban areas where consumption-based accounts have been calculated.

5. Policy implications and conclusions

While at a national level China, the UK and US have very different emissions profiles and mitigation priorities, our investigation of the carbon footprints of their urban centres reveals many common challenges. Specifically, in most urban areas in the UK and US, and in many urban areas in China, consumption-based emissions exceed production-based emissions. At the same time, correlations with income suggest that consumption-based emissions in Chinese urban centres could rise substantially, and rising consumption-based emissions are also associated with rising imports of embedded emissions across urban areas. A number of options, however, are available to policymakers at the urban level today. In contrast with a perception that affecting consumption-based emissions necessarily requires national level action on taxes and trade, at the local level urban areas could adopt a range of consumption-oriented policy and planning measures – relating for example to requirements for sustainable and durable infrastructure, for compact urban development, tougher building standards, improved procurement policies, promotion of the sharing economy or innovative waste management. Although the suite of urban options to address consumption-based emissions is comparatively under-researched, as the climate importance of urban areas continues to grow, and as more urban areas move from producer to consumer city status, the need to rapidly advance understanding, policy and practice in this field is readily apparent.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jclepro.2017.12.139.

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