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## EDITORIAL

## Systematizing and upscaling urban climate change mitigation

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The question of what cities can contribute to mitigation and adapting to climate change is gaining traction among researchers and policy makers alike. However, while the field is rich with case studies, methods that provide rich data across municipalities and potentially at global scale remain underdeveloped, and comparative insights remain scarce. Here we summarize contributions to the focus issue on ‘Systematizing and Upscaling Urban Climate Solutions’, also drawing from presentations given at an accompanying conference in 2018. We highlight four core areas for systematizing and upscaling urban climate mitigation solutions. First, with more and better (big) data and associated machine learning methods, there is increasing potential to compare types of cities and leverage collective understanding. Second, while urban climate assessments have mostly emphasized urban planning, demand-side action as related to both behavioral change and modified social practices relevant to urban space deserve more academic attention and integration across a diverse set of social sciences. Third, climate mitigation would be intangible as a single objective at the urban scale, and measures and solutions that coordinate mitigation coherently with adaptation and broader sustainable development goals require explicit conceptualization and systematization. Fourth, all insights should come together to develop governance frameworks that translate scientific exercises into concrete, realistic and organized action plans on the ground, for all cities.

**1. Introduction**

Urban research on climate change mitigation is increasingly gaining spotlight. Underlying driving forces include, on the one hand, the lack of international cooperation between nation states to substantially addressing the goals of the Paris agreement, and the hope that cities can help fill the gap with their relative operational ease. On the other hand, both academics and practitioners realize global strategies of climate change mitigation, while necessary, are clearly on their own insufficient in informing local stakeholders of how to tackle climate change; instead solutions that adapt to geographical and cultural contexts on the ground, and that match the political economy in place, are warranted.

Researchers awake to these trends and repeatedly call for building a global urban science Bai (2007, Solecki *et al* 2013, 2015, Creutzig 2015, Bai *et al* 2016, Acuto *et al* 2018). However, development towards such global urban science remains stuck in well-trodden paths, and the study of the global dimension of urbanization continues to focus on case studies, which is extremely important but on its own insufficient. Key barriers towards globalizing urban sciences involve data inconsistencies rendering city comparison difficult, and models either suited to country-scale global analysis, or to modeling individual city dynamics, but not to modelling ensembles of cities. They also include the lack of precise understanding of the similarities and differences between cities contexts, both on a socio-cultural aspect (differences in lifestyle and perceptions), and on an

environmental aspect (differences in exposure to climate change impacts for instance). A recent review outlines the existing state-of-the-art of available urban climate-change-relevant data and the different methodological approaches available for a quantitative global urban sustainability science (Creutzig *et al* 2019). However, such a quantitative/data-driven agenda must be integrated from the beginning with questions of goals, contexts, and non-quantitative data: how do mitigation and adaptation strategies come together? With questions of lifestyles and users: what urban solutions match the need, cultures, and desires of urbanites? And with questions of governance, such as: how can we adequately and securely govern big data driven solutions for climate change mitigation? These questions are repeatedly raised in recent literature, and more conceptual and empirical advances are called for (Bai *et al* 2018, Ürge-Vorsatz *et al* 2018).

In this focus issue, articles attempt to address some of these questions, investigating a) the potential of big data approaches to make urban sustainability research consistent and scalable; b) the role of urban inhabitants in shaping demand; c) the importance of relating mitigation and adaptation strategies; and d) how insights make action relevant in governance strategies (figure 1). Below we introduce their specific contributions.

## 2. Big data: typologies

Typologies have emerged as one key tool to bridge the gap between the urban and the locally specific, and the global effect, specifically global GHG emission patterns (Creutzig *et al* 2015, Shan *et al* 2018, Lamb *et al* 2019), and regional and national analysis of urban emission patterns (Hrabovszky-Horváth *et al* 2013, Baur *et al* 2013, Ahmad *et al* 2015, Baiocchi *et al* 2015). This focus issue comprises of several manuscripts that advance such typologies with the aim to systematize climate solutions.

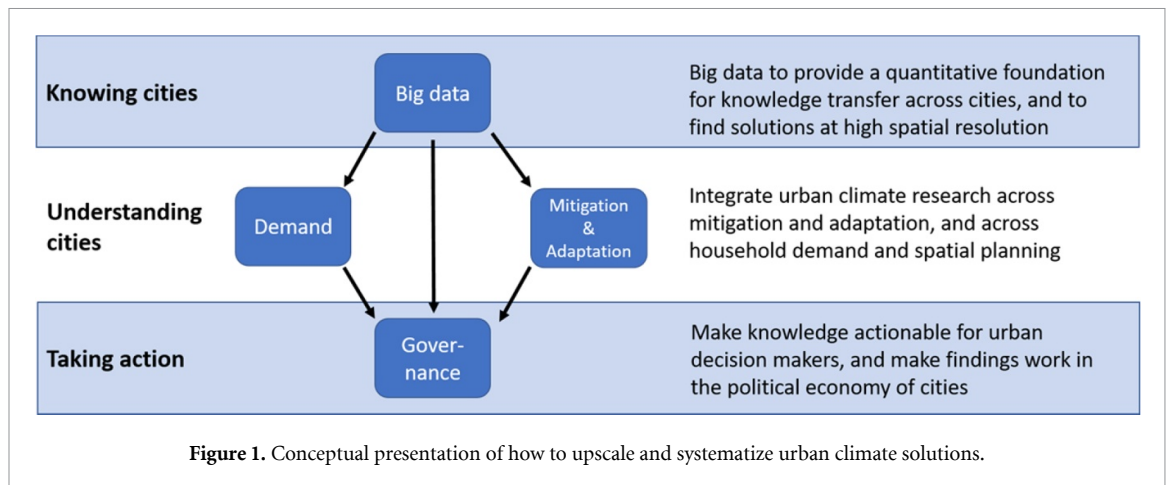
One of the most impressive is by Oke and colleagues, focusing on urban transport (Oke *et al* 2019). The authors make use of most recent data for 331 cities that comprise 40% of the world's population and are representative of all cities worldwide. Compressing a high-dimensional data set, they identify 12 types of cities that are characterized by 9 urban transport dimensions, involving mode specific characteristics (BRT, metro, or bikes), infrastructures (network, sprawl, congestion), and wider characteristics (population, development, sustainability). While the results are mostly as expected—car-dependent cities emit most CO<sub>2</sub>-emissions—the fine-grained information is relevant. Oke and colleagues rightly emphasize that the emerging congested cities, mostly in South and South-East Asia, which are still at low emissions

per capita but with rapid development, and the similarly rapidly developing Chinese cities, which could plausibly see an increase in bike sharing. These valuable results and data deserve further investigation in future research.

Big data approaches can equally be applied to both building and transport energy use in cities. For buildings, Gouveia and Palma assess dwelling stocks comprehensively using over half million Portuguese residential Energy performance certificates (EPCs) Gouveia and Palma (2019). They apply a building typology approach to investigate the potential for region-specific retrofitting actions as indicated by energy performance gaps. They demonstrate that roof retrofitting has the highest potential for energy reduction. This study demonstrates several potential applications of the EPC in the dwelling stock characterization and energy performance estimation for buildings retrofit, climate change mitigation, and thermal comfort.

In turn, Ahmad and Creutzig typologize energy use for commuting in India Ahmad and Creutzig (2019). Categorizing 640 Indian urban and rural districts according to the econometrically identified drivers of their commuting emissions, the authors demonstrate that per capita commuting emissions are influenced by the built environment and mobility-related variables. Income, urbanization, travel mode choice are shown to be the dominant classifiers of commuting emissions as well as high car ownership. The findings reveal that low-carbon commuting and development strategies require differentiation across geographical location and context. Solutions need to be tailored to geographical contexts with finer spatial clustering of determinants of commuting emissions. In rural areas, electric three-wheelers have potential to improve mobility, while keeping emissions low. In urban areas, high-quality bus rapid transit systems will help to fight traffic-related externalities. However, the socio-cultural status of cars, especially SUVs is an issue. The paper highlights the potential of context-stratified sustainable solutions emerging with the advent of big data.

These data-driven approaches are very promising. However, social science contributions, as developed in case studies, remain necessary to contextualize data-driven insights with issues such as political economy and cultural context, which is necessary for guiding action. It is fortunately possible to systematically relate quantitative data-driven approaches with case study insights systematically. Specifically, systematic search queries on literature inventories, such as Web of Science and Scopus, enable the identification of complete sets of case studies on specific cities (Lamb *et al* 2019). With such methods, it becomes possible to relate energy categorizations of city types (e.g. relationship between geographic zone and cooling demand) with human needs for thermal comfort



in specific places, and the policy response currently considered. One systematic scoping study, associated with this focus issue, made a next step in this endeavor, identifying 867 urban case studies on climate change mitigation that explicitly consider technological options or policy instruments (Sethi *et al* 2020). The authors find 41 different urban solutions, with relative abatement potential ranging between 5% and 105%. These kind of studies will continue to consolidate the knowledge base on urban climate solutions.

### 3. Demand

Research highlights that urban form strongly influences energy demand in buildings (Rode *et al* 2014). However, many aspects of the intersection between demand and urban characteristics remains scarcely explored.

One of the key concerns in a low carbon transition is whether a claimed reduction in resource intensity or increased environmental efficiency in a city is a genuine achievement or whether the environmental burden is transferred elsewhere. Accounting for embodied material and energy through trade is widely recognized as important, which has resulted in conceptual and methodological advances and increasing empirical evidences. This approach however, still leaves a loophole by only focusing on flows and not taking into account the existing stocks that are required to support productivity. The increasing role of the service sector in an economy is often considered to be a pathway to decoupling economic development and environmental impacts, but is it still the case if we take the existing stocks into account? Dombi's paper explores this question for the service sector in Hungary, using input-output data Dombi (2019). The result shows while the productivity of resource flows and the environmental impacts of the service sector did improve, the stock productivity has been either decreasing or, at best, showed little improvements. In other words, the improvements in

material flow productivity is coupled with intensive stock accumulation. The author suggests restructuring of production cost through reducing relative price for labor, innovativeness and other factors and increasing the relative price of natural resources through resource tax, as possible interventions.

Khosla and colleagues focus on another aspect of demand, that from appliances and their energy implications in India (Khosla *et al* 2019). They find that energy use and GHG emissions from appliances in India is only about a 3rd of world average, but that these patterns are rapidly changing as low-income households obtain modest economic capabilities and pursue energy services. As a welcome surprise, energy efficiency programs and consumer behavior results in high purchases and use of energy efficient lighting (LED) (see also Kamat *et al* (2020)). The same success, however, could so far not been replicated for fans, TV, and air conditioning (AC). The authors also demonstrate that behavioral factors, and not only housing-related material and socio-economic factors, such as income, are statistically relevant in explaining electricity consumptions. This not only reveals the importance of behavioral factors, such as choice architectures, in policy design, but also points to a largely unexplored area of research asking for the combined role of behavioral change and urbanization in high well-being low-energy demand trajectories.

In the wider context, a number of factors are all relevant in shaping energy demand, including building stock, demographics, and behavioral and social traits. For example, Niamir and colleagues find that these factors may lead to a threefold divergence in change in household electricity consumption in 2050, and thus economically divergent trajectories (Niamir *et al* 2020a). This implicates that universal policy instruments, such as carbon pricing, might be complemented by regionally stratified solutions that match local personal and social norms, but also education and structural dwelling factors (Niamir *et al* 2020b).

## 4. Mitigation and adaptation

Research on mitigation of and adaptation to climate change is often disparate, perhaps an unfortunate consequence of these topics being treated in two different volumes of the assessment reports of the Intergovernmental Panel on Climate Change, inadvertently serving as organizing platforms for communities. However, urban policymakers, having to deal pragmatically with issues (Barber 2013), intuitively understand better than others that action on mitigation and adaptation can be integrated in climate action plans (Reckien *et al* 2014, 2018). Following suit, the research community increasingly investigates action plans that jointly tackle both challenges, especially at urban level Ürge-Vorsatz *et al* (2018). This focus issue adds two specific contributions, both of them addressing measures to deal with heat waves, while keeping GHG emissions low.

Using a simple urban economic model, a paper by Pierer and Creutzig highlights how adaptation and mitigation have to be considered together when planning for urban infrastructures Pierer and Creutzig (2019), highlighted also in Nature Climate Change Wake (2019). The authors jointly model three aspects of urban form and their interactions: transport mode choice in a city; residential location choices of the inhabitants; and the cooling effect on temperature of urban parks during heat waves. Car use reduction to reduce transport-related GHG emissions (mitigation), and urban cooling to get adapted to heat waves (adaptation), are two commonly found policy targets at a city scale. The paper shows that considering both policy targets separately or together leads to widely different policy recommendations. The authors argue that a star-shaped city, involving high-density residential buildings along linear transport axes, are best suited to both reduce transport emissions and provide cooling from interjacent parks. The finding of the paper substantiates the claim that land-use planning is a central dimension to alleviate the trade-off between urban-scale climate adaptation and mitigation (Xu *et al* 2019).

Viguié and colleagues examine another important trade-off within the climate change debate: the consumption of energy for adaptation, taking the example of AC (Viguié *et al* 2020). Recent research shows AC plays an important role in energy-related behaviors of residents (Zhang *et al* 2020). Because of climate change, heat wave risk is increasing sharply. AC is an efficient tool to reduce the exposure to this risk, but it may lead to large energy consumption and worsen outdoor heat stress. By quantitatively studying the case of Paris, Viguié *et al* consider whether different cooling adaptation strategies at different scales could prevent the massive use of AC. They find that even ambitious strategies (large-scale city-wide urban greening; building-scale insulation policy and reflective roofs) do not appear sufficient

to totally replace AC and ensure thermal comfort, under a median climate change scenario. However, these suggested adaptation strategies can lead to significant reduction of AC energy consumption and of the heat released outdoors (which further drives up the demand for ACs), while keeping the same thermal comfort indoors. So do generalized behavioral changes in AC use. The paper makes the case for taking seriously the large increase in cooling energy consumption and heat-stress conditions posed by the increased number of extreme-heat days, and the resulting trade-off between energy consumption and maintaining indoor air temperature. The trade-off extends to the increased demand for water, which is significant to produce the projected required cooling. These results also show that adaptation actions, implemented early, may play a key role to remain on a low-carbon pathway.

## 5. Governance

The previous components of upscaling and systematizing—making best use of big data, integrating demand and urban planning, and adaptation and integration—will be futile if not made action-ready for municipal and other decision makers. This means understanding on the one hand institutional opportunities and obstacles to the development of efficient policies, and on the other hand the possibility of engagement and active participation of the local inhabitants to the climate strategy. This focus issue adds three contributions regarding these two aspects.

Sareen and Rommetveit use a living lab to study smart grids, with a view to problematize the common understanding of employing and scaling up technological infrastructure based solutions that do not account for local concerns and users' perspectives Sareen and Rommetveit (2019). Based on qualitative methods to investigate the roll out of smart meters in Norway, they draw insights based on the technical aspects, everyday practices, and political economy that underlie the motivation, engagement, participation and scale up of smart grids as an urban climate change mitigation strategy. They emphasize the need to balance out supply-side discursive power with localized practices, and focus on examining what motivates people to be energy efficient in different contexts. In doing so, they argue against misplaced expectations from the potential of 'smart' mitigation solutions and call for an alignment of local and systemic concerns, along with an understanding and addressing of interdependencies and trade-offs across scales to make substantial (rather than modest) changes for rapid mitigation. Specifically, democratic processes, citizen empowerment, and active engagement in technology development and adoption would all help to improve the usability and effectiveness of smart technologies.

**Table 1.** Summary of insights from this focus issue in all four categories, and outlook for further research.

	Insights from this focus issue	Outlook
Big data	<ul style="list-style-type: none"> <li>• Urban transport typologies reveal potential for climate policies that adapt to geographic context, emphasizing previously underrated modes, such as cycling and three-wheelers.</li> <li>• Roof retrofitting identified as key entry point for climate proofing buildings in Portugal.</li> </ul>	<ul style="list-style-type: none"> <li>• Use remote sensing and OpenStreetMap for refined typologies</li> <li>• Integrate typologies with household surveys (see also demand)</li> </ul>
Demand	<ul style="list-style-type: none"> <li>• Urban-scale climate policies are most effective when they integrate carbon pricing with policies that respect local social norms and dwelling characteristics.</li> <li>• Energy transitions are particularly important opportunities to leverage low-carbon lifestyles.</li> </ul>	<ul style="list-style-type: none"> <li>• Build typologies of demand-side transitions</li> <li>• Integrate urban form characteristics in these typologies</li> </ul>
Mitigation & Adaptation	<ul style="list-style-type: none"> <li>• Urban planning is a key tool to moderate problematic trade-offs between climate change mitigation and adaptation for heat waves.</li> </ul>	<ul style="list-style-type: none"> <li>• Investigate and model jointly optimized climate action plans for specific cities</li> </ul>
Governance	<ul style="list-style-type: none"> <li>• Users of ‘smart’ technologies should participate as active citizens.</li> <li>• Transport interventions can build on environmental attitudes, but work best when reflecting existing mobility patterns.</li> </ul>	<ul style="list-style-type: none"> <li>• Building differentiated action plans for many (all) cities that respect differences in social norms, spatial planning, and the political economy.</li> </ul>

Weiland and colleagues highlight how understanding people various behaviors and lifestyles choices, has important implications when designing climate policies in cities (Weiland *et al* 2019). A survey was conducted in the city of Potsdam, Germany, before the implementation of a large-scale trial policy aimed at reducing motorized traffic. The article analyzes the responses of 3553 participants to questions aiming at identifying their mobility behaviors and underlying attitudes within the context of this policy implementation. It shows that, through a cluster analysis, four groups can be identified, characterized by their mobility habits, attitudes towards the measure, and general level of environmental concern.

Groups involve i) car-oriented policy rejecters, ii) multimodal policy sceptics, iii) green-travel policy optimists, and iv) bike-dedicated policy-enthusiasts. The first two groups are quantitatively larger and strongly object to measures that reduce air pollution and that impair their existing mobility patterns. Each group presents specific attitudes and perceptions toward the policy, and instruments which can efficiently impulse behavioral changes in each group are different. A follow-up study of the same authors reveals that environmental attitudes are a main predictor of air quality policies in general, while existing and envisaged mobility patterns, especially bike use, are a main predictor of the specific policy suggested



for Potsdam (Schmitz *et al* 2019). Specific measures should hence always consider the mobility patterns of those affected.

Kim and Grafakos investigate the integration of mitigation and adaptation plans in Latin American cities Kim and Grafakos (2019). They find a moderate level of integration in most cities. They also demonstrate that learning from regional peer cities and donor agencies' input both help to promote the integration of climate plans.

## 6. Conclusions

Systematizing and upscaling knowledge about urban climate strategies is a key issue to address the goals of the Paris agreement. But the state of a global urban sustainability science is still in its infancy (Acuto *et al* 2018, Creutzig *et al* 2019). We present in this special issue a number of innovative studies (summarized in the table 1) which contribute to addressing the four main research gaps, which, we argue, exist in this field.

The first is how to know cities better (data issues). The second and third are how to compare what could be done in cities, both from a social-science perspective (e.g. upscaling demand-side policies) and from an environmental context perspective (e.g. integrating mitigation and adaptation perspectives). Finally, the fourth one is how to locally translate knowledge into action (governance issues).

Collectively, the papers that we present here show the path for a promising research agenda, which may be crucial to significantly reduce global emissions in the coming years.

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## References

- Acuto M, Parnell S and Seto K C 2018 Building a global urban science *Nat. Sustain.* **1** 2
- Ahmad S, Baiocchi G and Creutzig F 2015 CO<sub>2</sub> Emissions from Direct Energy Use of Urban Households in India *Environ. Sci. Technol.* **49** 11312–20
- Ahmad S and Creutzig F 2019 Spatially contextualized analysis of energy use for commuting in India *Environ. Res. Lett.* **14** 4
- Bai X, Dawson R J, Ürges-Vorsatz D, Delgado G C, Barau A S, Dhakal S, Leonardsen L, Masson-Delmotte V, Roberts D and Schultz S 2018 Six research priorities for cities and climate change *Nature* **555**
- Bai X 2007 Integrating global environmental concerns into urban management: the scale and readiness arguments *J. Ind. Ecol.* **11** 15–29
- Bai X, Surveer A, Elmquist T, Gatzweiler F W, Güneralp B, Parnell S, Prieur-Richard A-H, Shrivastava P, Siri J G and Stafford-Smith M 2016 Defining and advancing a systems approach for sustainable cities *Curr. Opin. Environ. Sustain.* **23** 69–78
- Baiocchi G, Creutzig F, Minx J and Pichler -P-P 2015 A spatial typology of human settlements and their CO<sub>2</sub> emissions in England *Glob. Environ. Change* **34** 13–21
- Barber B R 2013 *If Mayors Ruled the World: Dysfunctional Nations, Rising Cities* (New Haven, CT: Yale University Press)
- Baur A H, Thess M, Kleinschmit B and Creutzig F 2013 Urban climate change mitigation in Europe—looking at and beyond the role of population density *J. Urban Plan. Develop.* **140**
- Creutzig F, Baiocchi G, Bierkandt R, Pichler -P-P and Seto K C 2015 Global typology of urban energy use and potentials for an urbanization mitigation wedge *Proc. Natl Acad. Sci.* **112** 6283–8
- Creutzig F, Lohrey S, Bai X, Baklanov A, Dawson R, Dhakal S, Lamb W F, Mcphearson T, Minx J and Munoz E 2019 Upscaling urban data science for global climate solutions *Glob. Sustain.* **2** e2
- Creutzig F 2015 Towards typologies of urban climate and global environmental change *Environ. Res. Lett.* **10** 101001
- Dombi M 2019 The service-stock trap: analysis of the environmental impacts and productivity of the service sector in Hungary *Environ. Res. Lett.* **14** 065011
- Gouveia J P and Palma P 2019 Harvesting big data from residential building energy performance certificates: retrofitting and climate change mitigation insights at a regional scale *Environ. Res. Lett.* **14** 095007
- Hrabovszky-Horváth S, Pálvölgyi T, Csoknyai T and Talamon A 2013 Generalized residential building typology for urban climate change mitigation and adaptation strategies: the case of Hungary *Energy Build.* **62** 475–85
- Kamat A S, Khosla R and Narayanamurti V 2020 Illuminating homes with LEDs in India: rapid market creation towards low-carbon technology transition in a developing country *Energy Res. Soc. Sci.* **66** 101488
- Khosla R, Sircar N and Bhardwaj A 2019 Energy demand transitions and climate mitigation in low-income urban households in India *Environ. Res. Lett.* **14** 095008
- Kim H and Grafakos S 2019 Which are the factors influencing the integration of mitigation and adaptation in climate change plans in Latin American cities? *Environ. Res. Lett.* **14** 105008
- Lamb W F, Callaghan M, Creutzig F, Khosla R and Minx J 2018 The literature landscape on 1.5°C climate change and cities *Curr. Opin. Environ. Sustain.* **30**
- Lamb W F, Creutzig F, Callaghan M W and Minx J C 2019 Learning about urban climate solutions from case studies *Nat. Clim. Change* **9** 279–87
- Niamir L, Ivanova O and Filatova T 2020a Economy-wide impacts of behavioral climate change mitigation: linking agent-based and computable general equilibrium models *submitted*
- Niamir L, Ivanova O, Filatova T, Voinov A and Bressers H 2020b Demand-side solutions for climate mitigation: bottom-up drivers of household energy behavior change in the Netherlands and Spain *Energy Res. Soc. Sci.* **62** 101356
- Oke J B, Aboutaleb Y M, Akkinapally A, Azevedo C L, Han Y, Zegras P C, Ferreira J and Ben-Akiva M E 2019 A novel global urban typology framework for sustainable mobility futures *Environ. Res. Lett.* **14** 095006
- Pierer C and Creutzig F 2019 Star-shaped cities alleviate trade-off between climate change mitigation and adaptation *Environ. Res. Lett.* **14** 085011
- Reckien D, Flacke J, Dawson R J, Heidrich O, Olazabal M, Foley A, Hamann J-P, Orru H, Salvia M and Hurtado S D G 2014 Climate change response in Europe: what's the reality? analysis of adaptation and mitigation plans from 200 urban areas in 11 countries *Clim. Change* **122** 331–40
- Reckien D, Salvia M, Heidrich O, Church J M, Pietrapertosa F, De Gregorio-Hurtado S, D'alonzo V, Foley A, Simoes S G and Lorencová E K 2018 How are cities planning to respond to climate change? assessment of local climate plans from 885 cities in the EU-28 *J. Cleaner Prod.* **191** 207–19
- Rode P, Keim C, Robazza G, Viejo P and Schofield J 2014 Cities and energy: urban morphology and residential heat-energy demand *Environ. Plan. B* **41** 138–62

- Sareen S and Rommetveit K 2019 Smart gridlock? challenging hegemonic framings of mitigation solutions and scalability *Environ. Res. Lett.* **14** 075004
- Sethi M, Lamb W, Minx J and Creutzig F 2020 Climate change mitigation in cities: a systematic scoping of case studies *Environ. Res. Lett.* **15** 093008
- Schmitz S, Becker S, Weiland L, Niehoff N, Schwartzbach F and von Schneidmesser E 2019 Determinants of public acceptance for traffic-reducing policies to improve urban air quality *Sustainability* **11** 3991
- Shan Y, Guan D, Hubacek K, Zheng B, Davis S J, Jia L, Liu J, Liu Z, Fromer N and Mi Z 2018 City-level climate change mitigation in China *Sci. Adv.* **4** eaaq0390
- Solecki W, Seto K C, Balk D, Bigio A, Boone C G, Creutzig F, Fragkias M, Lwasa S, Marcotullio P and Romero-Lankao P 2015 A conceptual framework for an urban areas typology to integrate climate change mitigation and adaptation *Urban Clim.* **14** 116–37
- Solecki W, Seto K C and Marcotullio P J 2013 It's time for an urbanization science *Environment* **55** 12–17
- Viguie V, Lemonsu A, Hallegatte S, Beaulant A-L, Marchadier C, Masson V, Pigeon G and Salagnac J-L 2020 Early adaptation to heat waves and future reduction of air-conditioning energy use in Paris *Environ. Res. Lett.* **15** 7
- Wake B 2019 Optimal city design *Nat. Clim. Change* **9** 499–499
- Weiland L, Schmitz S, Becker S, Niehoff N, Schwartzbach F and von Schneidmesser E 2019 Climate change and air pollution: the connection between traffic intervention policies and public acceptance in a local context *Environ. Res. Lett.* **14** 085008
- Xu L, Wang X, Liu J, He Y, Tang J, Nguyen M and Cui S 2019 Identifying the trade-offs between climate change mitigation and adaptation in urban land use planning: an empirical study in a coastal city *Environ. Int.* **133** 105162
- Zhang Y, Bai X and Mills F P 2020 Characterizing energy-related occupant behavior in residential buildings: evidence from a survey in Beijing, China *Energy Build.* **214** 109823
- Ürge-Vorsatz D, Rosenzweig C, Dawson R J, Rodriguez R S, Bai X, Barau A S, Seto K C and Dhakal S 2018 Locking in positive climate responses in cities *Nat. Clim. Change* **8** 174–7