

Cities and regions tackle climate change mitigation but often focus on less effective solutions

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Although the potential for cities and regions to contribute to global mitigation efforts is widely acknowledged, there is little evidence on the effectiveness of subnational mitigation strategies. Here we address this gap through a systematic review of 234 quantitative mitigation case studies. We use a meta-analytical approach to estimate expected greenhouse gas emissions reductions from 12 categories of mitigation strategies. We find that strategies related to land use and development, circular economy, and waste management are most effective and reliable for reducing emissions. The results demonstrate that cities and regions are taking widespread action to reduce emissions. However, we find misalignment between the strategies that policymakers and researchers focus on, compared to those with the highest expected impacts. The results inform climate action planning at the city and regional level and the evaluation of subnational climate targets.

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There is growing recognition that subnational governments (administrative units below the level of a national government, such as cities, states, and provinces¹) play an important role in global climate change mitigation. The recent IPCC Sixth Assessment Working Group III report includes two chapters that discuss subnational actors' potential contributions to mitigation^{2,3}. Subnational actors also present a unique mitigation opportunity, since they have jurisdiction over key emissions sources and activities, such as energy systems, waste management, land use, and transportation and building infrastructure^{2,4,5}. Many subnational actors have pledged to address climate change⁶, offering potential to help fill the gap between national policies and global goals to limit warming to 1.5 °C or below^{3,7–9}.

Few studies have systematically evaluated subnational mitigation actions and their impact on emissions. These aggregate analyses across subnational governments are challenging, due to the difficulty of comparing mitigation efforts across varying spatial levels, circumstances, and capacities of cities and regions¹⁰. Yet, this information is critical to help decision makers at all levels of government to develop and evaluate effective plans to achieve mitigation goals and improve coordination between levels^{11,12}. Previous studies on subnational climate action have used climate action plans or voluntary reporting platforms to evaluate the goals and planned strategies of subnational actors, but typically focus on the quantity and ambition of targets rather than the implementation and impacts of climate actions^{8,13–17}. Case studies that evaluate mitigation strategies in specific contexts are numerous and the systematic review and analyses of subnational case studies can offer insights into the relative effectiveness of various mitigation approaches^{18–20}.

Meta-analysis, which combines and analyzes data from multiple studies on a particular topic to identify patterns, trends, and overall effects, is an approach that enables aggregation and generalization of findings from case studies, which is particularly relevant for studying subnational mitigation actions where localized studies are a predominant research method. Systematic review and meta-analytic methods have been applied in a variety of climate and environmental research areas, including urban land expansion²¹, climate change impacts^{22,23}, and others^{24–29}. A few studies have applied meta-analytical methods to assess mitigation strategies. Some have focused on strategies' mitigation potential within certain sectors or contexts^{30,31}. Others have evaluated the landscape of urban case studies or climate mitigation policies, focusing more on qualitative characteristics, such as their topical and geographic distribution, rather than quantitative emissions reductions^{18,32}. We identified only one study that compared quantitative emissions reductions across a range of sectors and strategies, focusing specifically on relative emissions reductions within urban contexts¹⁹.

In this study, we leverage the findings from quantitative subnational mitigation case studies to estimate the expected emissions reductions from a range of mitigation strategies and evaluate actions being taken by cities and regions. To the best of our knowledge this is the first study to focus on subnational mitigation strategies at multiple jurisdictional scales. After screening nearly 300,000 search results from Scopus and Web of Science, we identified 234 subnational climate change mitigation case studies that report quantitative emissions reduction impacts. From these articles, we extracted 1413 emissions reduction impacts and a variety of meta-data for each impact (including the mitigation strategy, subnational context, and study methodology), referred to as the full dataset. This process is summarized in Fig. 1 and described in detail in the Online Methods.

Within the full dataset ($n = 234$), we identified 779 impacts from 137 comparable studies (the synthesis dataset), synthesized

the reported impacts from these studies, and estimated emissions reduction impact ranges for 12 types of mitigation strategies. Using the results of this meta-analysis, we ranked strategy categories based on their expected effectiveness and certainty of emissions reductions. We found that strategies related to land use and development, circular economy, and waste management are most effective. We also identified reported impacts from 49 studies where study authors evaluated mitigation strategies that have been implemented or planned by subnational governments (as opposed to those proposed by such governments, implemented by other actors, or evaluated only for research purposes). From these studies, we recorded data on 134 specific subnational government actions, referred to as the actions dataset ($n = 49$), and found that policymakers use a wide range of strategies and policy instruments, but are not choosing strategies based on the size or reliability of expected emissions impacts.

Results

Overview of subnational case study literature. Figure 2 shows the relationships between mitigation strategies, sectors, and categories and the relative quantities of each in the full dataset. Building and transportation sector strategies appeared most frequently (23% and 22% of observations, respectively), while interventions in the industrial sector were the least studied (5%). Waste, agriculture, forestry, and land use, and electricity and heat accounted for the remaining 50% of observations. Here, cities include local governments with jurisdiction over a specific territory, such as towns, districts, and counties. Regions are defined as subnational administrative units that are broader than a municipality and often are the highest administrative level below the national government, such as a province, prefecture, or state^{1,8}. For cities, waste and water treatment practices were the most common category, while agriculture and farm practices were the most popular for regions. Building and transportation categories such as building construction and improvement, building energy and heat systems, and clean vehicle transportation frequently appear in both urban and regional case studies.

Geographical coverage of subnational climate actors in the full dataset is shown in Fig. 3. There are 242 unique subnational actors appearing in the full dataset, where approximately 55% are cities and 45% represent regional governments. Certain geographic areas and actors are overrepresented in the subnational case study literature. We found that studies tend to focus on subnational actors in North America (34%), East Asia and the Pacific (27%), and Europe (15%). Studies from developed countries comprise the majority of the sample of studies evaluated - only one third of impacts (37%) occurred in the Global South³³.

Subnational climate action. The actions dataset includes 134 government actions from 49 case studies that analyze mitigation strategies that have been implemented or planned by subnational governments. Within the actions dataset, we found 100 mitigation strategies enacted by 50 unique actors (39 cities and 11 regions). The geographic distribution of action mirrors the broader case study literature, but is even more concentrated in North America, Asia, and Europe, with only 1 strategy identified in both Latin America and Africa. Subnational actors have implemented or planned a wide range of mitigation strategies—two-thirds of the strategy options we considered in this analysis (26 of 38 strategies) and all 13 categories were identified in the actions dataset. Based on the government actions that appear in case studies, transportation strategies are used most frequently by governments (40 of 100 strategies) followed by cross-sectoral and waste sector strategies. We find differences in the types of

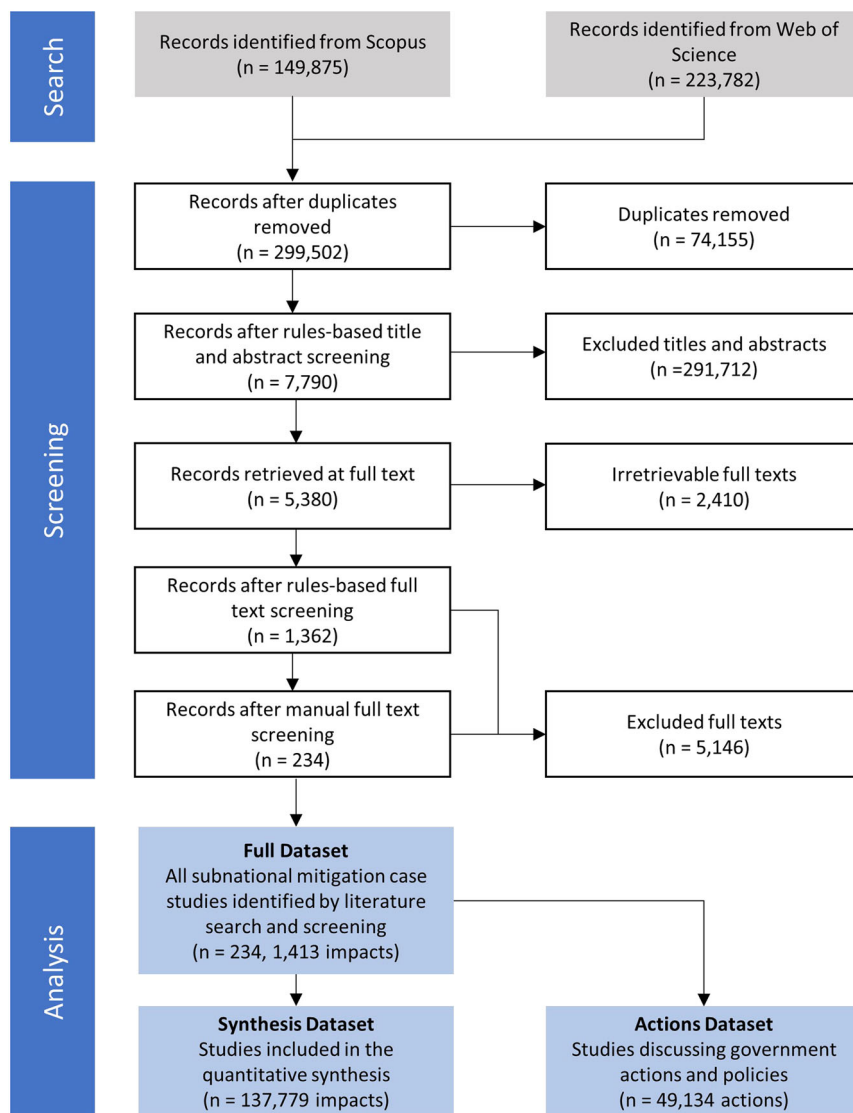


Fig. 1 Literature search and screening flow diagram. Each box includes the number (n) of unique studies present at that step of the analysis. The shaded blue boxes in the “Analysis” section representing the final analysis datasets also include the number of observations in each dataset. Observations in the full dataset and synthesis dataset are emissions reduction impacts, while observations in the actions dataset are subnational government actions.

strategies implemented in geographic regions (i.e., North America, Latin America and the Caribbean) – cross-sectoral strategies were the most popular in Asia, while transportation strategies dominated in North America and Europe.

For each government action, we identified the type of policy instrument used to implement the mitigation strategy^{34,35}. Figure 4 demonstrates the frequency of subnational climate actions by sector and policy instrument type, revealing patterns in the types of instruments used in each sector. In transport and waste, policy support and direct investment actions dominate. Direct investment includes investments in both infrastructure and public assets, while policy support refers to institutional creation or planning activities that strengthen enabling conditions³⁴. Transport and waste were also the only two sectors where education and information instruments appeared. Building sector strategies focus more on behavioral change through technology adoption and rely heavily on financial incentives and regulatory instruments like building codes and efficiency standards. The results suggest that subnational governments strategically use different policy instruments to mitigate emissions in different sectors, which has been demonstrated for national climate

policies and behavioral interventions^{34,36}. Although most of the government actions in the dataset are attributed to cities (78%), we find that regional governments used more economic and regulatory instruments (63% of regional actions), while cities relied more on direct investment and policy support (66% of city actions).

Emissions reduction impact ranges. We estimate expected emissions reduction ranges for 12 categories of mitigation strategies using the synthesis dataset (n = 137). The results are reported in annualized, per-capita metrics tons of CO₂ equivalent. For example, the expected emissions reduction impact across the entire synthesis dataset was 0.26 tons CO₂e capita-1 year-1 with a standard deviation of 0.05 (0.26 ± 0.05). To get a sense of the magnitude of the emissions reductions reported in the following sections, we demonstrate how this average expected emissions reduction impact would compare to the aggregate baseline emissions and GHG mitigation targets of two subnational actors – Buenos Aires, Argentina and British Columbia, Canada. According to CDP, British Columbia has a population of around 5 million and reported 2007 baseline emissions of 63.8 million

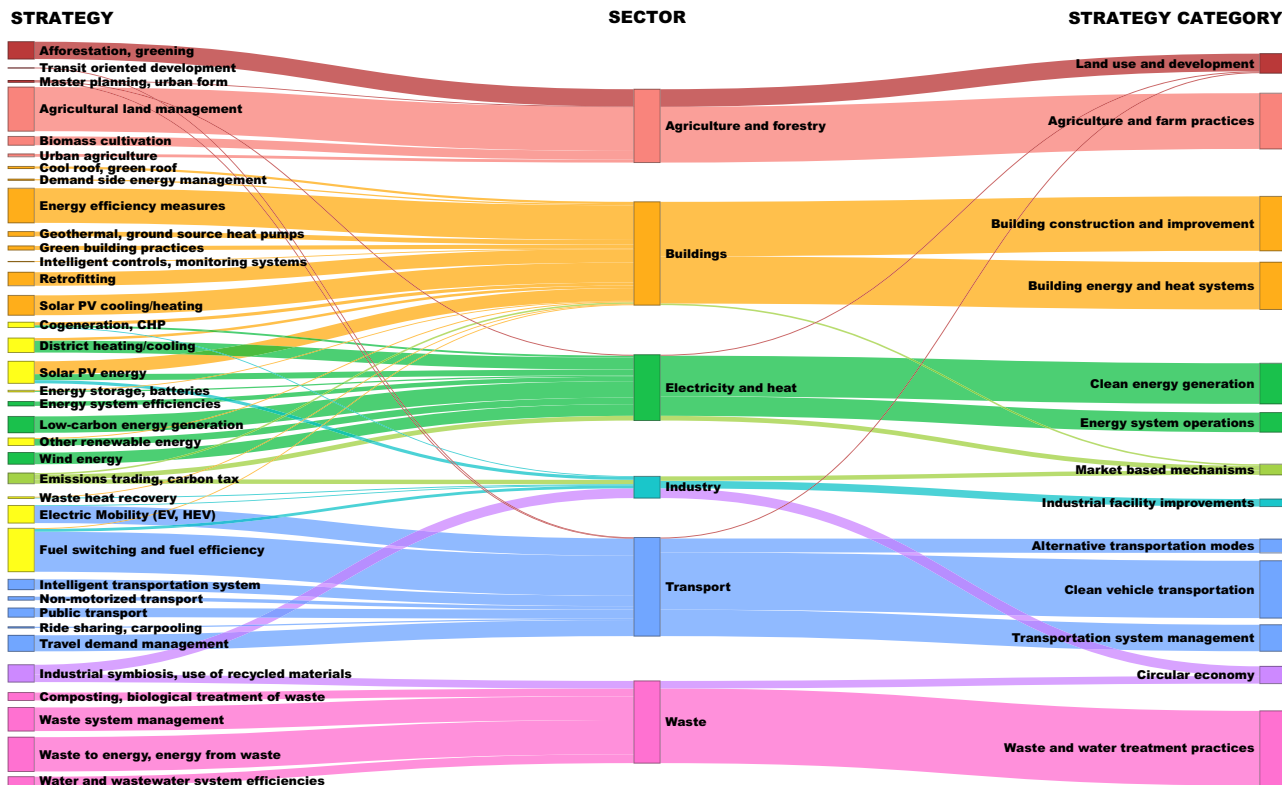


Fig. 2 Sankey diagram of emissions reduction impact observations in the full dataset ($n = 1413$). The left column represents mitigation strategies, the middle column represents sectors, and the right column represents categories, which include 10 sector-specific categories and 3 cross-sectoral categories. The width of a given node or link indicates the proportion of total emissions reduction impacts assigned to that grouping. Note that this refers to the count of impacts within each group, not the total emissions reduction value. Link and node colors show the final category assigned to that set of impacts, except for yellow nodes, which indicate strategies that are assigned to final categories in more than one sector. For example, case studies evaluated the implementation and use of solar PV across multiple sectors (building, energy, and industry) and this strategy appears in three categories: building energy and heat systems, clean energy generation, and industrial facility improvements.

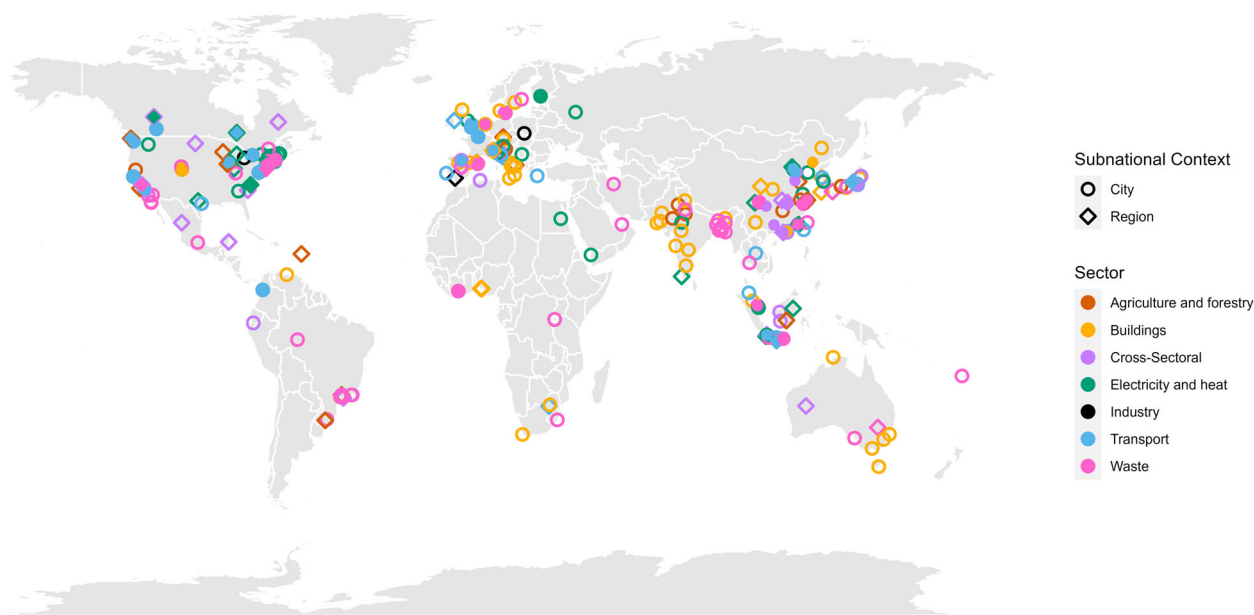


Fig. 3 Map of all subnational actors appearing in the full dataset ($n_{actors} = 242$). Actor type is indicated by shape (circles represent cities and diamonds represent regions). Color signifies the sector of the mitigation strategy observed. The filled points indicate the locations of government actions that have been implemented or planned by subnational actors observed in the actions dataset ($n_{actors} = 50$).

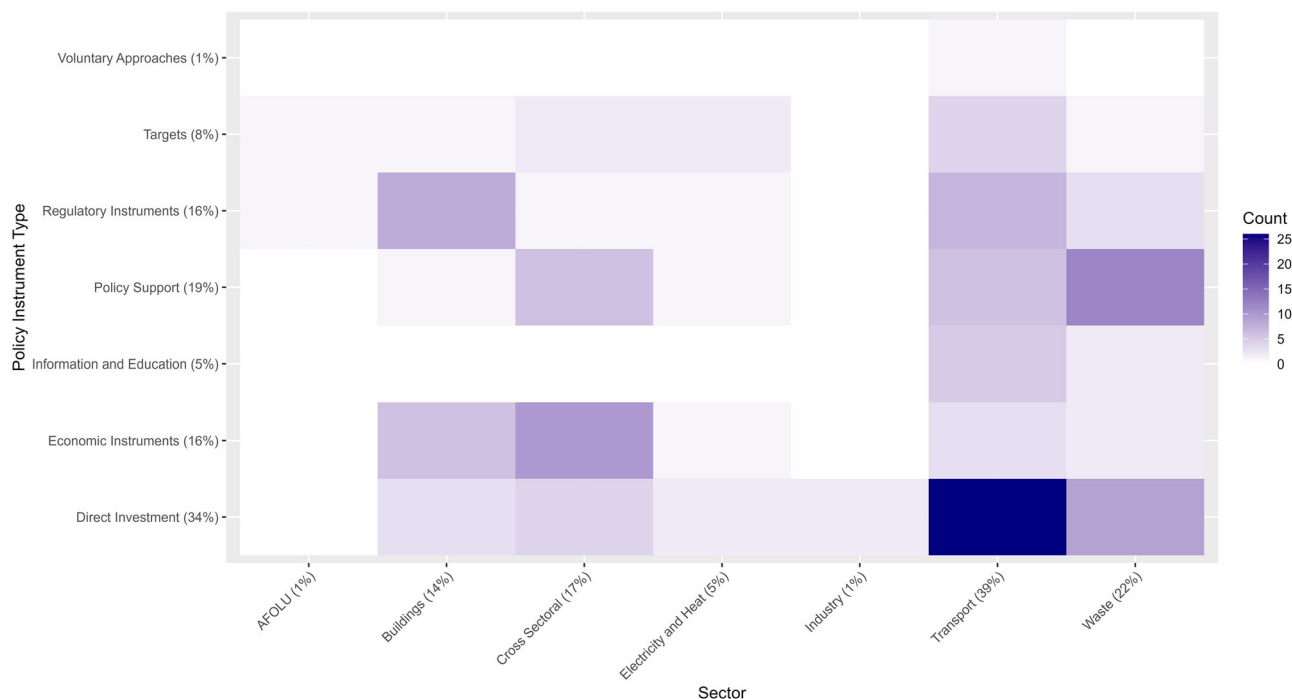


Fig. 4 Subnational climate actions by sector and policy instrument type in the actions dataset ($n_{\text{actions}} = 134$). Shading represents the number of implemented or planned actions observed by sector and policy instrument type within the actions dataset ($n_{\text{actions}} = 134$). Each label includes the percentage of total action observations attributed to that sector or policy instrument type. Note that the total of percentages by sector and policy instrument type may not add up to exactly 100% due to rounding. Additional details on the types of actions observed are included in Supplementary Table 3.1.

tCO₂e³⁷. A mitigation strategy that reduces emissions by 0.26 tons CO₂e capita-1 year-1 would represent a 2% annual reduction from baseline emissions, compared to British Columbia's target to reduce their emissions by 40% by 2030³⁷. For Buenos Aires, which has a population of around 3 million and 2015 baseline emissions of just over 13 million tCO₂e, the same 0.26 tons CO₂e capita-1 year-1 reduction would equate to a 6.2% reduction in annual city-wide emissions, compared to their target to reduce emissions by 53% by 2030³⁸. To compare uncertainty in the emissions reduction impacts between categories, we also report the coefficient of variation (CV) as a measure of relative data dispersion, which is estimated as the standard deviation divided by the bootstrap mean for each strategy category^{39,40}.

Cross-sectoral strategy categories were considered separately from sector-specific categories since they may include some sector-specific strategies and often apply to a broader set of relevant actors and activities than sector-specific categories. The results for the nine sectoral categories and three cross-sectoral categories are presented in Figs. 5 and 6. In the following sections, we discuss the results from sector-specific and cross-sectoral categories in more detail and develop a ranking of strategies based on these results.

Sector-specific categories. Mitigation strategies that focus on electricity and heat have the highest expected emissions reductions and greatest uncertainty amongst sector-specific categories (Fig. 5B). Clean energy generation and energy system operations had average emissions reduction impacts of 0.44 ± 0.18 and 0.37 ± 0.14 tons CO₂e capita-1 year-1, respectively. Coefficients of variation for these categories were 37.6% for energy systems operations and 41.0% for clean energy generation, both close to the average coefficient of variation (CV) across all categories of 39.3%. Transportation and building sector strategy categories had the smallest expected emission reductions. Transportation system

management was the only exception, with average emissions reductions of 0.17 ± 0.06 tons CO₂e capita-1 year-1, although this category is under-studied (only 8 studies), compared with the average number of studies per category (16 studies) that we included for synthesis. Over 85% of the impacts in this category were related to travel demand management strategies intended to reduce vehicle miles traveled by residents. Alternative transportation modes had the lowest expected emissions reductions overall with high certainty at 0.03 ± 0.01 tons CO₂e capita-1 year-1. Clean vehicle transportation had slightly higher average reductions but had the greatest uncertainty among all categories with a coefficient of variation of 72%.

Building sector strategies appeared frequently in the full dataset, but more than two-thirds of buildings studies were excluded from the synthesis because the impacts could not be standardized (primarily due to the scale of the intervention). Expected impacts from building sector categories were small relative to other categories but building construction and improvement strategies had much lower uncertainty compared to building energy and heat systems, with CVs of 21% and 43%, respectively. Industrial facility improvements was the smallest category in the full dataset and impacts from only one study were able to be standardized, due to variation in the contexts, units, and scale of industrial strategies. Although industrial facility improvements were difficult to compare and evaluate, industrial sector interventions were prevalent in the cross-sectoral categories.

Cross-sectoral categories. The cross-sectoral strategies include circular economy (industrial symbiosis, use of recycled materials), land use and development (afforestation and greening, master planning, transit-oriented development), and market-based mechanisms (emissions trading, cap-and-trade, carbon tax). Land use and development resulted in the highest expected

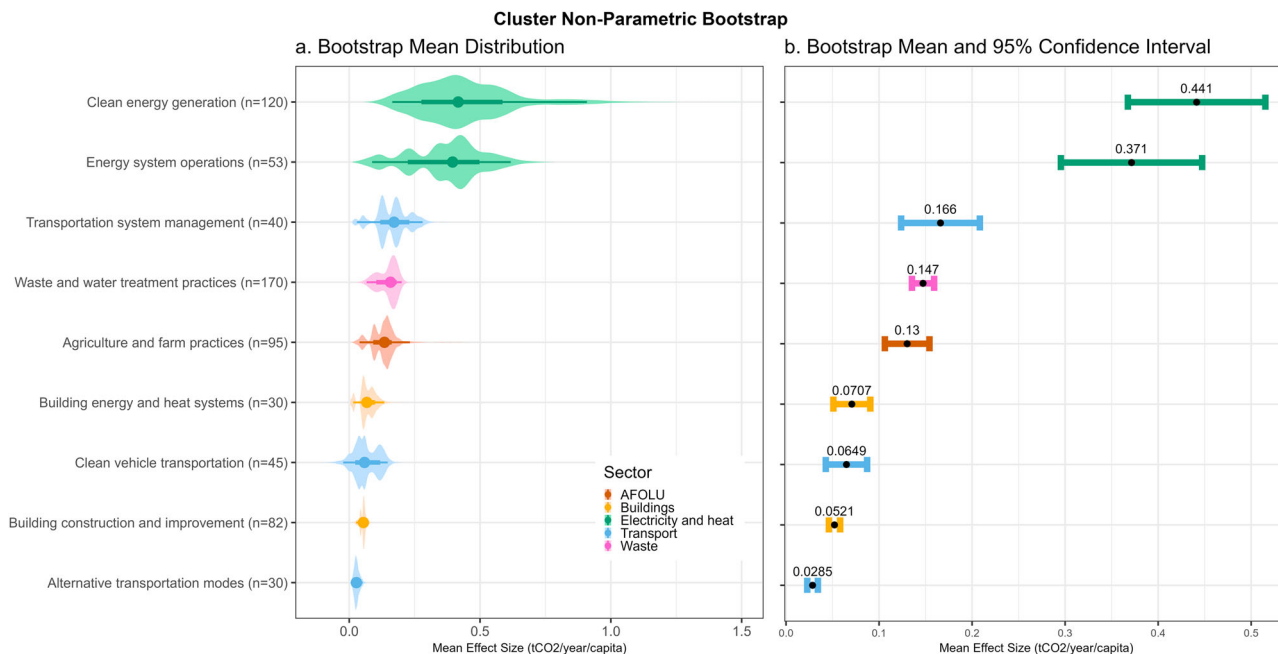


Fig. 5 Expected emissions reduction ranges for sector-specific mitigation strategies categories. The labels for each category include the number of emissions reduction observations for each category that were used in the bootstrapping analysis. Colors indicate the different sectors of each mitigation strategy category. **a** Bootstrap sampling distribution of the mean emissions reduction impact for each category. **b** The bootstrap mean emissions reduction impact and 95% confidence interval for each category.

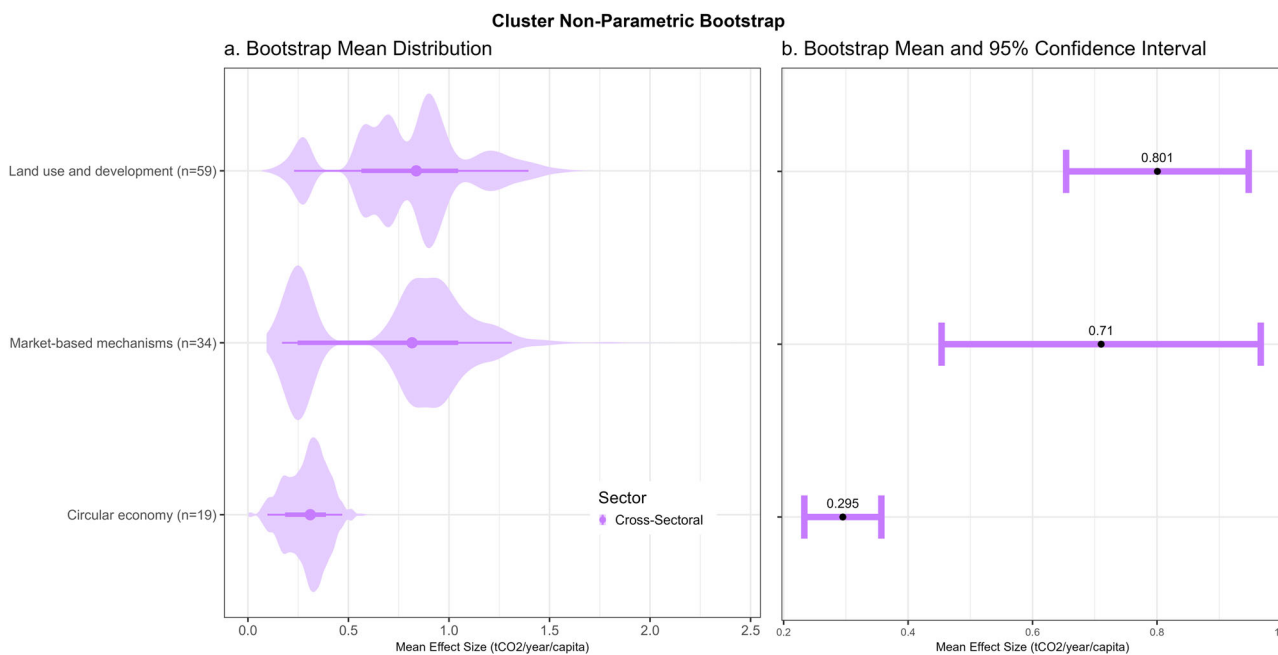


Fig. 6 Expected emissions reduction ranges for cross-sectoral mitigation strategies categories. The labels for each category include the number of emissions reduction observations for each category that were used in the bootstrapping analysis. **a** Bootstrap sampling distribution of the mean emissions reduction impact for each category. **b** The bootstrap mean emissions reduction impact and 95% confidence interval for each category.

emissions reductions at 0.80 ± 0.30 tons CO₂e capita-1 year-1. Nearly 90% of the impacts in this category were related to afforestation or greening, which were also the main driver of variation, likely due to differences in the scale at which these interventions can be implemented based on available land area. The average emissions reduction associated with market-based mechanisms was 0.71 ± 0.37 tons CO₂e capita-1 year-1. Market-based mechanisms were only evaluated within four countries – Canada, China, Japan, and the US – across 8 studies in the

synthesis dataset. Market-based mechanisms also had high uncertainty compared to other cross-sectoral and sectoral categories, with a CV of 52%. The circular economy category included strategies promoting industrial symbiosis systems and the use of recycled materials across the industrial and waste sectors. The expected impact range for this category was 0.30 ± 0.10 tons CO₂e capita-1 year-1. This category ranks lower than other cross-sectoral categories but higher than most sector-specific categories, with impacts similar to electricity and heat sector categories.

Category ranking. The results reveal that categories vary in relative effectiveness (based on the mean emissions reductions) and relative uncertainty (based on the coefficients of variation). This information can be used to compare and rank mitigation strategy categories. As an example, we considered a simple ranking where effectiveness and uncertainty are weighted equally. We find that two cross-sectoral categories, land use and development and circular economy, rank highly across both effectiveness and uncertainty. Waste and water treatment strategies ranked third overall, due to low uncertainty for this category.

While we chose to weight the two characteristics equally, different weighting schemes could be applied here depending on the priorities of the decision maker. For example, building construction and improvement and market-based mechanisms both fall to the middle of our overall ranking, but these strategies are nearly opposite in their effectiveness and uncertainty rankings. Under different weighting schemes, we would expect one of these categories to rise in the rankings, while the other would fall towards the bottom. We also considered if the magnitude or reliability of expected impacts aligned with the types of strategies implemented by governments, but we did not find statistically significant correlations between the prevalence of categories and the ranking of categories in terms of effectiveness and uncertainty. This result indicates a misalignment between the strategies that subnational governments have pursued (represented within the case study literature) and the mitigation potential of those strategies and suggests that other policy characteristics and motivations might take precedence in the choice of mitigation strategies.

Discussion

Understanding subnational climate mitigation strategies and their impacts is critical for allowing urban and regional policymakers to identify best practices and where investments may yield the greatest returns by way of emissions reductions. Despite their substantial potential mitigation contributions, scarce research synthesizing across studies that evaluate city and regional governments' climate efforts has been conducted. We screened nearly 300,000 studies and identified 234 subnational climate change mitigation case studies reporting absolute emissions reductions. We standardized and synthesized impacts from these studies to estimate the relative effectiveness of subnational mitigation strategies. Most studies estimated potential rather than achieved emissions reductions, providing further evidence for the lack of ex-post evaluations on climate policies^{11,20}. We also identified and ranked 12 mitigation strategy categories in terms of the magnitude and relative uncertainty of expected absolute emissions reductions. Within the case study literature, we found differences between the types of strategies that have received the most attention from researchers and policymakers and those with the greatest mitigation potential.

The results of the meta-analysis reveal potential tradeoffs between the effectiveness and certainty of emissions reductions from subnational mitigation strategies. We developed a simple ranking of strategy categories where effectiveness and uncertainty are weighted equally, but policymakers and researchers could develop their own rankings depending on their priorities. We find that strategies related to land use and development, circular economy, and waste and water treatment practices rank highly in both characteristics. In general, cross-sectoral strategy categories (e.g., land use and development, circular economy, and market-based mechanisms) had higher expected emissions reductions than single-sector categories, which aligns with findings from other studies and provides additional support for IPCC recommendations^{3,19,41,42}. Among single-sector strategies,

electricity and heat sector categories had high mitigation potential compared to other categories. Ranking strategy categories based on the certainty of impacts reveals a different ordering. Building construction and improvement and waste and water treatment practices had the lowest relative uncertainty.

The rankings of strategy categories presented here are exclusively based on emissions reductions demonstrated through case studies and should not be interpreted or used as a definitive preference over strategies. Emissions reductions are just one of the important factors to consider when choosing between mitigation strategies. In particular, cities and regions face limitations in their choice of mitigation strategies due to differences in their governance capacity and their degree of control over emissions, which can vary substantially from one country to another⁴³. Regional governments have more extensive authority over critical functions such as energy supply and transportation infrastructure, compared to municipal governments^{43,44}. The dominant sectoral sources of emissions also vary across subnational governments, where Scope 1 emissions generally include direct emissions from within the actor's territory due to transportation, industry, waste, and local energy generation and Scope 2 includes energy generation from outside of the actor's boundary⁴⁵. Studies have found that the sectoral breakdown of emissions for subnational actors varies by geography, development status, and urban growth typology^{3,46}. Policymakers can use these results to compare and benchmark the expected impacts of different strategies but should not rely on these findings alone in their decisions.

Our ranking of mitigation strategies based on absolute emissions reductions and relative uncertainty differs from rankings appearing in similar studies^{19,31}. Several factors can help explain these differences. Our study focuses on subnational governments at multiple jurisdiction scales, rather than just cities, which have received more recent attention for their potential role in climate mitigation. In the synthesis, we only included strategies that were studied at a subnational-wide scale, to more closely represent the emissions reductions that could be achieved if these strategies were implemented through policy. Our study also considered absolute rather than relative emissions reductions, which convey information about both baseline emissions and reductions and are key for comparing mitigation strategies³¹.

Within the case study literature, we find misalignment between the mitigation strategies that have been studied and translated into policy most frequently and those that rank highly in effectiveness and uncertainty. We find that cities and regions are taking action to reduce emissions across sectors but are not prioritizing strategies that have the largest expected impacts or lowest uncertainty. This finding could suggest that other policy characteristics and motivations are more important to policymakers when considering mitigation options. Subnational actors may be constrained in their ability to pursue high-impact strategies due to lack of resources, complexity of implementation, and political viability. The broader literature encourages local governments to shift away from fossil fuels, reduce the carbon intensity of electricity, and reduce energy consumption in buildings and transport, which may require action from higher levels of government or the private sector to coordinate with and support subnational governments^{3,4}.

Policymakers in local and regional governments must also balance their climate goals with other important objectives and these other objectives may act as the primary motivation for the implementation of a mitigation strategy. For example, policymakers might choose to implement a waste management strategy to improve cost-effectiveness and sanitation or update their building efficiency standards to promote public health and safety. In these hypothetical cases, mitigation is not the primary goal, but occurs as a secondary benefit or co-benefit. Similarly, cities and

regions may be pursuing mitigation as a primary goal, but choosing mitigation strategies that provide specific co-benefits or synergies with other goals. Cities and regions may prioritize strategies that achieve co-benefits to enable climate action in the face of political opposition⁴³. We find that mitigation strategies that appeared frequently in the actions dataset align with those that have been more frequently studied for both mitigation and adaptation benefits⁴⁷. Notably, two of the most popular strategies in the actions dataset – alternative transportation modes and clean vehicle transportation – were at the bottom of the rankings for expected emissions reductions. Yet transportation mitigation strategies are demonstrated to have considerable potential for co-benefits with adaptation, air quality, and public health^{47,48}.

We also find differences in the sectoral distribution of strategies between the full dataset (all case studies; $n = 234$) and actions dataset (studies evaluating government actions; $n = 49$). In the full dataset, we find that waste strategies are studied most in cities, while agricultural strategies are studied most frequently in regions. This reflects key differences in jurisdiction and governmental responsibility between cities and regions. In general, cities tend to have authority over waste and water systems, while regions are more likely to include rural and agricultural areas within their territory^{35,36}. Energy, building, land use, and transportation regulations might occur at either the regional or local levels^{36,41,42}.

In the actions dataset, transportation strategies dominate (40% of observations) and are especially popular in Europe and North America, while cross-sectoral strategies are more prevalent in Asia. We also find that cities and regions appear to rely on different policy instruments when implementing mitigation strategies, with cities using more direct investment and policy support and regions relying more on economic and regulatory instruments. This finding appears to align with traditional divisions of responsibility and historic differences in municipal and regional approaches to climate action, with cities focusing on reducing emissions within their own operations and indirect policy support, while regions are more likely to align with country-level approaches and directly address community-wide emissions through regulations and incentives^{43,49}. Collectively, the differences in mitigation strategies identified across the three datasets suggest that more information is needed to understand subnational policy choices over mitigation strategies.

The findings of this study are subject to several limitations. Meta-analyses often seek to control for study quality based on reported error metrics, however most studies included in this analysis did not report them. The variation in methodologies used in the case studies also means that the authors defined baseline or counterfactual scenarios in different ways and controlled for any confounding factors to different extents. To account for this potential variation in study quality, we developed alternative weights and tested three additional synthesis specifications. We confirmed that the overall size and ranking of expected impacts remains consistent across all specifications (Supplementary Discussion 1). We recognize that both cities and regions are heterogeneous, and the strategies evaluated in this study take place at different spatial scales and under different contexts. We try to improve comparability by only evaluating strategies that were implemented at a subnational-wide scale and then standardizing impacts by population. While this study is focused on subnational mitigation strategies, we acknowledge that various economy-wide actions are taken at the national level. Due to limitations in sample size, we were not able to further break down the synthesis analysis of mitigation strategy categories by other classifications, like actor type (cities vs. regions) or global regions, but this would be an interesting direction for future work. We also chose to treat mitigation strategies autonomously but recognize that

interactions between strategies can lead to synergies or trade-offs in emissions reductions^{13,50}. We also did not consider the costs of implementing mitigation strategies. Both costs and strategy interactions may be important factors in subnational governments' choice of mitigation strategies. We used regression analysis to test if within-category variation in impacts is associated with factors related to the subnational context or study design and found that most factors were not significantly associated with the size of emissions reductions (Supplementary Discussion 2). Other factors that could not be explicitly tested here may also explain the relative uncertainty of impacts within each category or policymakers' choices over strategies, such as the power of actors over emitting activities, the scale of implementation, and existing mitigation action. A useful direction for future research would be to develop measures for these characteristics and evaluate their relationship with expected emissions reductions.

Conclusions

This study presents a comparative assessment of the absolute emissions reductions from subnational climate mitigation strategies and provides a detailed picture of subnational climate action, as represented in the subnational case study literature. We focus on mitigation strategies that have been evaluated within the jurisdiction of cities and regions, so that the results can directly inform climate action planning at the subnational level. The results reveal that there are substantial differences in the size and certainty of emissions reductions from different types of mitigation strategies, which can be used for ranking and comparison. Our evaluation of subnational climate action demonstrates that cities and regions are taking action to reduce emissions across sectors, but that policymakers are not choosing strategies based on the size or certainty of expected impacts. The analysis also provides insights into climate action by identifying government actions that have appeared in subnational case studies. The study highlights the ongoing need for ex-post evaluation of climate mitigation strategies. More research is needed to understand how factors beyond context and study design contribute to variation in expected emissions reductions between mitigation strategies and policy choices.

Methods

Overview. The methods used for the systematic literature review and evidence synthesis are discussed briefly here and detailed in the following sections. We conducted keyword searches in Scopus and Web of Science to identify potentially relevant studies. The searches and initial removal of duplicate results from the two databases yielded 299,502 articles. We then further de-duped and filtered to articles that were published in 2010 or later and referred to a specific city or region in their abstracts, using the ClimActor harmonized dataset and R package. This initial processing resulted in a set of 51,562 articles. Articles were then screened for eligibility, first on abstracts and then on retrievable full text articles, using automated rules-based filtering and n-gram analysis in R. To be eligible for inclusion, each study must: (1) report numeric impacts to GHG gas emissions, (2) evaluate a strategy intended to reduce GHG emissions, (3) report impacts within the jurisdiction of a subnational (city or regional) government, and (4) report on the results of primary research. The automated screening process resulted in a set of 1362 articles, which were then manually screened by members of the research team, resulting in a final set of 234 eligible subnational mitigation case studies. From this final set of articles, we extracted and coded 1413 emissions reduction impacts and supporting meta-data.

In order to synthesize the extracted evidence, the emissions reduction impacts needed to be standardized. The effect statistic

for this analysis was emissions reductions in annualized, per-capita metric tons of CO₂ equivalent (metric tons CO₂e capita⁻¹ year⁻¹). We were able to standardize impacts from approximately 58% studies (137 studies) and 55% of the data (779 impacts), while the remaining data did not provide all information needed to standardize the impacts to annualized, per-capita metric tons of CO₂ equivalent. We used clustered, non-parametric bootstrapping to estimate the average emissions reduction impact and confidence interval for each mitigation strategy category^{21,51,52}.

Database search. The literature search strategy expanded off of methods previously used to identify urban case studies^{18,19}. Keyword searches in Scopus and Web of Science were used to identify studies that had both a subnational term and a mitigation term in their title, abstract or keywords. The search strings used in Scopus and Web of Science are shown in Supplementary Table 4.1, with subnational terms and mitigation terms joined by “AND”. We did not limit by document type, in order to include both peer-reviewed and gray literature, such as books and conference papers. This keyword search yielded 149,875 results in Scopus as of January 2022 and 340,687 results in Web of Science as of March 2022. The article results were downloaded from Scopus and Web of Science, then de-duped by article title, journal, and year. In the initial data processing, the research team also removed duplicates of articles that were identified in both Scopus and Web of Science. After these initial processing steps were complete the dataset included 299,502 articles, with 149,016 from Scopus, 216,746 from Web of Science, and 66,260 articles that appeared in both the Scopus and Web of Science searches.

Article screening. After identifying a set of potentially relevant articles based on keyword searches, we filtered the dataset to a subset of articles that specifically mentioned the name of a subnational actor in the title or abstract. This approach also aligns with the literature search process used in similar studies, which used the GeoNames database to filter down to articles that mentioned a city or urban location name with at least 15,000 inhabitants in the title or abstract^{18,19}. Since we wanted to capture other subnational government actors (such as states and regions) and not just cities, the dataset was filtered using the ClimActor dataset and R package and the definitions used for cities and regions were aligned with those used by ClimActor^{1,8}. ClimActor is the largest harmonized dataset of city and regional governments that have participated in climate action networks, such as the Global Covenant of Mayors for Climate and Energy and C40 Cities initiative¹. Furthermore, since the ClimActor dataset is intended to be used for data harmonization, it includes multiple possible names for over 27,000 subnational actors. This prevents us from excluding articles where the authors may not have used the most common name for a specific subnational actor. After filtering for articles that mentioned a subnational actor name in the title or abstract, there were 79,572 articles remaining. During this processing step, we observed that there were still a number of duplicates in the dataset and performed a second round of de-duping, based on article title only. We also removed any articles that had erroneously flagged a publisher name or location as a subnational actor by removing articles that had flagged a subnational actor name after the copyright symbol in the abstract and removed studies that were published prior to 2010. After these steps, 51,562 articles remained.

The articles were then screened using pre-determined eligibility criteria, first on abstracts and then on the full article texts. To identify subnational climate change mitigation studies with quantitative emissions reduction impacts, we established the following eligibility criteria:

1. The study must include quantitative emissions reduction impacts to greenhouse gas (GHG) emissions, reported in numeric form.
2. The reported emissions impacts must be associated with an intervention or strategy intended to reduce GHG emissions.
3. The reported impacts must be associated with a specific subnational government (city or regional) context.
4. The reported impacts must be the result of original research conducted in the study.

To screen article abstracts, three members of the research team screened a sample of 50 articles for eligibility based on their abstracts. We developed a list of topical keywords that indicated relevance to greenhouse gas emissions and positive keywords that indicated impacts to GHG emissions. We also established a list of stopwords that signified ineligibility and identified broad subnational terms from ClimActor that did not refer to specific actor names. These four sets of terms are listed in Supplementary Table 4.2. First, we excluded articles with stopwords terms in the abstract or title (18,305 articles), then we removed articles that had been flagged with a broad subnational term (928 articles). We used N-gram analysis to screen the remaining articles. First, we generated bigrams from the abstracts of all remaining articles. The list of bigrams was filtered using the topical terms and then the positive terms, so that the remaining bigrams included one topical and one positive term. The final list of 593 bigrams and the frequency with which they appeared in the article abstracts is included in Supplementary Table 4.3. We used this list of bigrams to filter the articles, aiming to identify articles that discussed impacts to emissions in their abstracts. This filtering process yielded 7790 articles. From this set of articles, we were able to retrieve 5380 full text PDF documents. Full text articles were then screened using a similar, rules-based strategy. Two random samples of 50 articles were selected for manual screening – one to develop a screening strategy and the other to test the performance of the final strategy. The final strategy identified articles with at least 2 references to “co2” that were located within 40 characters of a number, aiming to identify articles reporting quantitative emissions impacts. This strategy was then applied to all articles, resulting in a final set of 1362 articles. The remaining articles were screened manually for eligibility by members of the research team, resulting in a final set of 234 articles.

Data extraction and standardization. After identifying the final set of subnational mitigation case studies, we extracted the emissions reduction impacts and meta-data from the articles. Although the studies included in the analysis rely on a variety of different methodologies, we assume that the data inputs used were accurate and that the chosen methodologies were implemented correctly, so that the resulting emissions reduction estimates from the studies are reliable. Each emissions reduction impact was recorded as an individual observation. If the article directly reported a reduction, then we extracted this exactly as it was reported in the article. If the article did not directly report a reduction, but instead reported emissions levels under a baseline or business-as-usual scenario and one or more mitigation scenarios, then we calculated the reduction as the difference between reported baseline and scenario emissions for each mitigation scenario. We collected data related to the impact, the mitigation intervention, the subject of the intervention, the study methodology, and the subnational context. We also coded additional fields, such as the sector, mitigation strategy, and subnational actor type. We did not specifically collect baseline emissions data from the articles, unless we calculated the reduction based on reported baseline and scenario emissions. A full list of the variables that were collected is reported in Supplementary Table 4.4.

For each impact, we captured details about the specific climate change mitigation intervention and categorized it into one of six sectors and one of 38 mitigation strategies, based on classifications used in similar studies^{18,19}. The list and definitions of these mitigation strategies are in Supplementary Table 4.5. In the full dataset, 36 of 38 possible mitigation strategies appeared. The two strategies that did not appear in any study were parking management-expansion, park & ride and walkability & pedestrianization. The sector-mitigation strategy pairings were assigned to one of 13 mitigation strategy categories by sector (Supplementary Table 4.6). For articles that discussed government actions and policies, a separate data extraction was conducted to record data on all the actions described in the article, even if they were not associated with a specific emissions reduction impact. We hosted two in-person workshops and one asynchronous workshop where student volunteers assisted in extracting data from the articles. Student volunteers assisted in collecting data from 20 articles, with each article being screened by two students to ensure data quality. We extracted 1413 emissions reduction impacts from the 234 studies, with 6.04 impacts reported per study on average.

To synthesize the results, we needed to convert the extracted impacts to a standard metric, which we defined as emissions reductions in annualized, per-capita tons of CO₂ equivalent (tonsCO₂e capita-1 year-1). Positive values indicate reduced emissions, while negative values indicate that emissions actually increased under a given strategy. Although all studies in the final dataset reported quantitative emissions reduction estimates, not all impacts were able to be standardized. Observations fell into one of four categories, based on two characteristics. The first characteristic related to the units of the reported impacts – about three quarters of studies reported per-time impacts, meaning they reported emissions reductions over a certain time frame, which were simple to annualize using the time frame of the impact. The remaining quarter of studies reported per-unit impacts, where the emissions reductions are reported in relation to another quantity, such as building area (ex. tons CO₂ m⁻²) or waste production (ex. tons CO₂ per ton of municipal solid waste). It was possible to convert the per-unit impacts to per-time impacts if: (1) the study reported details on the type, value, and units of the subject of the study, such as total building area or the amount of municipal solid waste produced in the year, and (2) the units of the emissions reduction impact aligned with the study subject units (ex. the study reported emissions reductions in tons CO₂ m⁻² year-1 and reported the total building area in m²). Studies that did not report the information needed to convert the per-unit impacts to per-time impacts were excluded from the standardization. The second characteristic was related to the scope of the impact related to its subnational context, since the standard metric was reported per-capita. We chose to include observations where the mitigation strategy was applied to the entire subnational context or a specified portion of the subnational context (nearly 60% of observations) to reflect the perspective that a subnational actor might take when considering potential mitigation strategies. We excluded observations where it was unclear how the scope of the study related to the subnational actor. By this distinction, we would include an observation where a strategy was applied to 10% of all residential buildings, but exclude an observation where a strategy was applied to 10 buildings. This distinction ensures that the impacts of the included strategies were comparable in scale, could be attributed to the whole subnational population (as a per-capita impact), and were intended to represent the types of strategies that might be considered and implemented by a subnational actor. Note that this does not mean that all observed impacts in the synthesis dataset are attributable to subnational government actions (this is

analyzed separately in the actions dataset). Eligible observations were standardized using the report impact units, time frame, subnational actor population, and study subject values and units (where necessary). Subnational actor populations were taken from the ClimActor dataset and supplemented with desk research as needed.

We were able to standardize 779 observations (55%) from 137 studies (59%), which comprise the synthesis dataset and are used in the meta-analysis. As a validity check, we compared the standardized emissions reduction impacts to the subnational actor's country-level per-capita emissions. Of 779 total observations, just 10 (1.3%) had standardized emissions reduction impacts higher than country-level per-capita emissions. All 10 observations were in a city context – which tend to have higher per-capita emissions – and were projecting potential emissions reductions in future years (2025 or later), under assumptions that emissions would be higher in the future. Summary statistics for the standard metric, annualized, per-capita tons of CO₂ equivalent, are reported in Supplementary Table 4.7.

Synthesis and analyses. We used non-parametric, cluster bootstrapping to derive the mean value and distribution of standardized emissions reductions across 12 mitigation strategy categories. Non-parametric bootstrapping is a flexible statistical technique for estimating uncertainty around a point estimate that does not rely on distributional assumptions and can be applied to finite samples, making it a popular option for meta-analyses^{21,53,54}. The standard non-parametric bootstrap method assumes each observation is independent. In our dataset, we cannot make this assumption, since many of the studies report multiple emissions reduction impacts that are likely dependent due to similar methods, context, and assumptions within each study. To account for this dependence at the study level, we selected the cluster bootstrapping technique, also known as the pairs cluster bootstrap, to account for within-group dependence at the study level⁵². For each mitigation strategy category, we resampled studies with replacement up to the original number of studies for that category, keeping all observations for each study that is selected. Then we compute the mean value of emissions reductions across all observations in the resample and repeat this process 10,000 times to derive a bootstrap sampling distribution for each category. The reported mean value and confidence intervals are drawn from the bootstrap sampling distribution. Using the standard deviations from the bootstrapping, we also estimated the coefficient of variation (CV) for each strategy category to facilitate comparisons across categories. The coefficient of variation is a relative measure of data dispersion, estimated as the standard deviation divided by the bootstrap mean for each category^{39,40}.

Reporting summary. Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The original search results from Scopus and Web of Science and all data collected from the final set of studies are available in a public GitHub repository (<https://github.com/datadrivenenvirolab/meta-analysis-quantifying-subnational-mitigation-solutions/>).

Three files were too large to be stored on GitHub and are available in a Google Drive Folder (<https://drive.google.com/drive/folders/1A1ToAzzx9pQDJaIPRYO-SVru1FWtWzM?usp=sharing>). The folder is also linked in the README file on the GitHub page. There are no restrictions on the availability of this data. Data on country-level sectoral emissions comes from World Emissions Clock by World Data Lab for 2022 (<https://worldemissions.io/>)⁵⁵ and ClimateWatch for 2019 (<https://www.climatewatchdata.org/ghg-emissions>)⁵⁶. Subnational actor populations, latitude, and longitude come from the ClimActor R package and dataset (<https://github.com/>)

datadrivenenvirolab/ClimActor)^{1,57} and were supplemented with internet desk research if missing. Country-level population data comes from World Development Indicators for the World Bank for 2019 and 2021 (<https://databank.worldbank.org/source/world-development-indicators>)⁵⁸.

Code availability

All code to reproduce the analysis and figures is available in R Version 4.2.2 in a public GitHub repository at <https://github.com/datadrivenenvirolab/meta-analysis-quantifying-subnational-mitigation-solutions/>.

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Author contributions

K.B.F. contributed to the data collection, cleaning, analysis, writing, editing, and revisions. K.S. contributed to the collection, analysis, writing, editing, and revisions. Z.Y. contributed to the data collection, cleaning, and analysis. E.J. contributed to the data collection, analysis, editing, and revisions. A.H. contributed to the conceptual development, writing, editing, and revisions.

Competing interests

The authors declare no competing interests.

Additional information

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