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Using cost–benefit analyses to identify key opportunities in demand-side mitigation

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Demand-side mitigation relies on individuals' and households' willingness to alter their consumption habits and daily routines to reduce their carbon footprint. Despite optimistic forecasts for well-being improvements, broad adoption of these behavioural changes remains elusive. Our study analyses 12 behaviours in Beijing, China, using a cost–benefit approach that includes both tangible (pecuniary) and intangible (non-pecuniary) benefits. Our findings indicate that eight behaviours result in individual-level welfare loss. Even after accounting for mitigation benefits, seven behaviours still incur social-welfare loss. Monte Carlo simulations unveil substantial variability in welfare impacts, highlighting opportunities for targeted policy interventions. Depending on the perspective (individual versus societal) and the goal (welfare versus mitigation), we recommend four demand-side practices for Beijing policymakers. In addition, we propose actionable steps on the basis of sensitivity analyses. This study underscores the need for an objective and universally applicable framework to evaluate demand-side behaviours and optimize emissions reduction potential.

The concept of demand-side mitigation is straightforward. Many daily activities of individuals and households contribute to GHG emissions[1]. As such, climate advocates across various tiers of society have promoted behavioural changes (for example, switching to electric vehicles, adopting meat-free diets) that can reduce one's carbon footprint. While seemingly innocuous, the footprints of these activities are substantial as household consumption accounts for approximately two-thirds of global emissions[2]. Furthermore, demand-side approaches are projected to reduce GHG emissions in end-use sectors by 40–70% (ref. 3).

In a rare attempt to comprehensively assess how climate-friendly behaviours affect well-being, multiple climate experts concluded that nearly 80% of demand-side mitigation and well-being combinations are beneficial[4].

Despite the promising outlook for demand-side mitigation, uptake remains stubbornly low[4–6]. One plausible explanation is that pro-climate behaviours are not as beneficial for individuals' welfare as earlier thought as these behaviours affect well-being in both pecuniary and non-pecuniary manners. Towards this end, we conduct a cost–benefit analysis (CBA) to better understand how individuals' welfare is affected by demand-side mitigation behaviours. In this regard, this study aligns with a body of work that has scrutinized the welfare implications of well-meaning environmental policies[7–11].

Early studies in behavioural economics and psychology laid the groundwork for demand-side mitigation, showing that simple interventions such as peer comparisons can reduce energy consumption[12] or that non-price interventions can encourage pro-environmental behaviours[13–15]. However, many interventions fail to sustain long-term behavioural changes and often target trivial actions with minimal climate benefits[16–19].

Another strand of work focused on comparing the emissions mitigation impacts of these behaviours[20–22]. Studies suggested a disparity between advocacy and effectiveness in developed countries, where low-impact behaviours are often prioritized over more impactful ones[23]. While they did not fully explore plausible explanations, they suggested focusing on behaviours that are most effective at reducing personal emissions rather than on low-impact and easy-to-perform ones.

A key knowledge gap across these strands of literature is that they have yet to comprehensively examine the trade-offs and

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Table 1 | Selected climate mitigation behaviours with cost–benefit components

Category	Behaviour	(1) Pecuniary components	(2) Non-pecuniary components
Transportation	Switch from private vehicle to public transportation	Purchase costs	Time costs
		Maintenance costs	Psychological costs
		Travel costs	
	Switch from ICEV to BEV	Purchase costs	Search and wait costs for charging
		Maintenance costs	
		Fuel costs	
	Shift from short-distance flight to HSR	Travel costs	Time costs
			Delay and cancel costs
Energy	Turn off ACs during peak hours in summer	Electricity consumption costs	Discomfort costs
	Shift from the cheapest to the most energy-efficient appliances	Purchase cost	
		Electricity consumption costs	
	Turn off lights in every room	Electricity consumption costs	Attention costs
Diet	Switch from animal protein to tofu	Purchase costs	Psychological costs
	Switch from animal protein to plant-based meat (PBM)	Purchase costs	Psychological costs
	Eliminate use of disposables in takeouts	Purchase costs	Time costs for cleaning
Lifestyle	Maximize waste sorting and recycling		Time costs for waste sorting
	Switch from plastic bags to reusable bags for shopping	Shopping bag usage costs	Attention costs
	Switch from paper books to e-books	Book purchase costs	
		Reading device costs	

These demand-side mitigation behaviours are those commonly advocated by the Beijing local government and local non-governmental organizations. Without loss of generality, we assume that behavioural changes take place completely. For example, shift from private to public transportation means that the individual will commute entirely by public transportation.

decision-making process from the protagonist's viewpoint. Current evidence consistently shows that pro-environmental attitudes motivate individuals to take low-cost actions and have little effect on high-cost behaviours[24,25]. Environmental health research also suggests that adoption of beneficial technologies (for example, improved cookstoves, improved toilets) is contingent on low user costs[26,27]. It is hence reasonable to assume that individuals will adopt climate-friendly behaviour only if it improves their well-being. In this regard, an important starting point for encouraging demand-side mitigation is to understand the cost–benefit trade-offs individuals face.

In this Article, we consider 12 demand-side mitigation behaviours commonly advocated by Beijing's local stakeholders (Table 1) and conduct CBAs from the viewpoint of an individual. These analyses inform the welfare implications of each behaviour and provide insights into feasible policy levers.

A key challenge in CBA is monetizing non-pecuniary costs and benefits (for example, discomfort from public transport, search time for electric-vehicle charging stations). We use established non-market valuation methods to translate these into dollar equivalents[28–30] and verify our estimations with a representative survey of Beijing residents.

Our study contributes to climate mitigation literature by addressing key gaps. Recognizing that end consumers account for around 70% of GHG emissions, we apply CBA—a tool rarely used in demand-side mitigation—to offer objective and replicable evidence into cost–benefit outcomes, which in turn can shape effective policies[31]. Focusing on Beijing, our detailed exploration of demand-side behaviours yields findings applicable to urban China and major global cities, with our methodological framework adaptable to various locations. In addition, we advance discussions on emissions mitigation and carbon pricing by assessing the social-welfare implications and abatement costs of different behaviours, providing crucial insights for policymakers evaluating demand-side strategies.

Welfare implications of demand-side mitigation

We begin analysing the welfare implications of demand-side mitigation using Monte Carlo simulations as this method utilizes (almost) all combinations of parameter values to compute welfare.

First, we see that 8 of 12 pro-climate behaviours reduce individual welfare, ranging from ¥9 (Chinese yuan) to ¥3,180 person^{-1} yr^{-1} (Table 2). The remaining four behaviours confer positive welfare changes between ¥20 and ¥951 person^{-1} yr^{-1}.

Second, due to disparities in preferences, income and ease of adoption, it is likely that these averages conceal substantial heterogeneity. We deduce from distribution of welfare changes across 10,000 simulations (Fig. 1) that waste sorting, turning off air conditioners (ACs), switching to plant-based proteins and switching to reusable bags are unlikely to benefit Beijing residents under current conditions as their individual-welfare distribution is predominantly negative. However, there are several behavioural changes where their averages are masked by wide heterogeneity. For example, while electric-vehicle adoption presents the highest average gain, further policy interventions are still necessary as a large proportion (45%) of results yield welfare losses. It is noteworthy that several behaviours display bimodal distributions, suggesting that segments of the population, on the basis of socioeconomic status (SES) or preferences, are more likely to benefit/lose from behavioural changes. For example, for switching from animal protein to tofu, individuals with vegetarian tendencies and lower meat consumption are more likely to benefit vis-à-vis meat lovers.

The rationale behind many pro-climate behaviours incurring individual-welfare losses is clear when demarcated by cost type. Across many behaviours, pro-climate actions often result in monetary savings. However, the non-pecuniary costs (for example, psychological and time costs) are larger, and overall welfare decreases when considered together. Failure to assign equal attention to non-pecuniary costs may thus result in overestimating the individual-welfare gains of demand-side mitigation (Fig. 2).

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Table 2 | Cost effectiveness of demand-side mitigation behaviours

Demand-side mitigation behaviour	(1) Private-welfare change (¥ person^{-1} yr^{-1})	(2) CO_2e saved (kg person^{-1} yr^{-1})	(3) Benefits of emissions mitigation (¥ person^{-1} yr^{-1})	(4) Social-welfare change (¥ person^{-1} yr^{-1})	(5) Abatement cost (¥ tCO_2e^{-1})
Private to public transportation	−2,448.9	486.1	629.5	−1,819.4	5,037.9
ICEV to BEV	951.2	152.2	197.1	1,148.2	−6,250.6
Short-distance flight to HSR	64.6	371.8	481.5	546.0	−173.6
Turn off ACs during peak hours in summer	−1,582.8	217.2	281.3	−1,301.5	7,286.6
Turn off lights in every room	20.2	36.3	47.1	67.3	−555.9
Cheapest to energy-efficient appliances	−31.9	14.5	18.8	−13.1	2,196.8
Animal protein to tofu	−114.6	147.3	190.8	76.2	778.0
Animal protein to PBM	−3,179.7	131.3	170.1	−3,009.7	24,214.0
Eliminate disposables utensils in takeouts	−5.4	0.5	0.7	−4.8	10,548.7
Waste sorting and recycling	−238.6	34.8	45.0	−193.5	6,859.9
Plastic to reusable bags	−9.0	4.1	5.3	−3.7	2,195.5
Paper books to e-books	186.6	19.1	24.8	211.4	−9,749.0

Column (1) shows the average welfare change at the individual level. Column (3) computes the benefits of emissions mitigation by using a social cost of carbon of US\$185 tCO_2e^{-1} (ref. 32). Column (4) is computed by aggregating columns (1) and (3). Column (5) is computed by dividing column (1) by column (2).

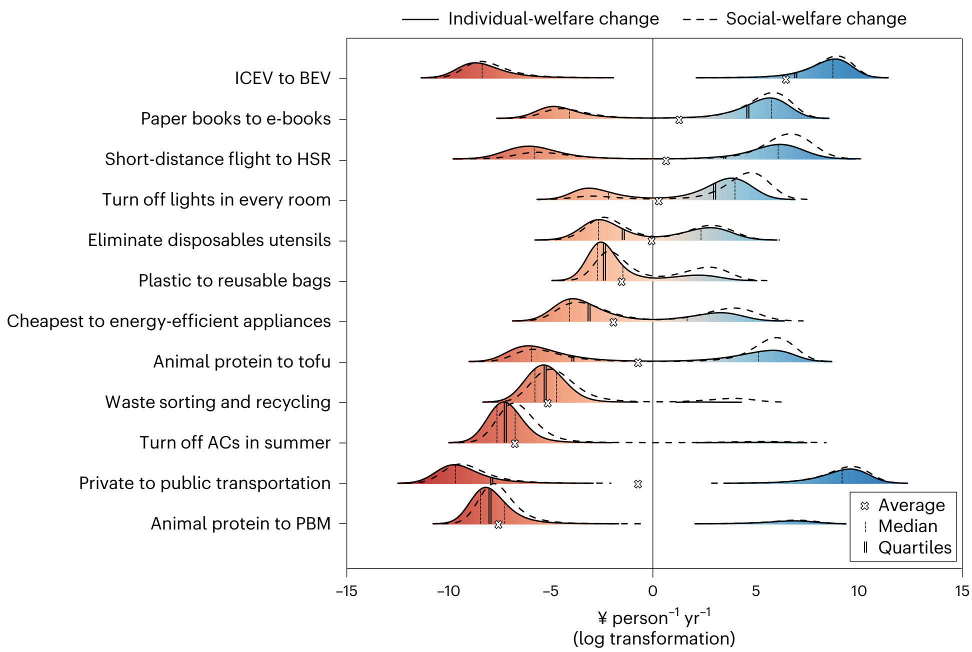

Fig. 1 | Distribution of individual-welfare change estimates. Kernel density plots of welfare changes across 12 demand-side mitigation behaviours as obtained from 10,000 simulations of randomly drawn parameters. The horizontal axis is log-transformed welfare change. The solid and dashed curves are kernel density functions for individual and social-welfare changes, respectively. Vertical double lines and dashed lines indicate the 25th and 75th percentiles and the median of welfare changes, respectively. Crosses indicate the average of welfare changes. Areas shaded red and blue indicate welfare losses and gains, respectively.

Third, while individual-level welfare is ostensibly important to residents, policymakers may want to include the social benefits of mitigation. We compute the CO_2-equivalent (CO_2e) saved person^{-1} yr^{-1} for each behaviour (Supplementary Section 1) and multiply this emissions reduction by a recently estimated social cost of carbon (SCC): US\$185/ tCO_2e (ref. 32). While the social-welfare loss of engaging in demand-side mitigation is now lower at ¥358 yr^{-1} (Table 2), closer examination shows that across the eight behaviours that imposed individual-welfare losses, seven are still detrimental to societal welfare (the exception being from meat to tofu). As a thought experiment, we further compute the minimum SCC needed for all demand-side behaviours to yield at least a non-negative societal welfare change to be hefty at US\$3,460 tCO_2e (Supplementary Section 2).

To partially address concerns that our results may be different from actual experiences, we surveyed Beijing residents and asked them to rate the pecuniary and non-pecuniary costs of the 12 pro-climate behaviours on a 5-point Likert scale. By consolidating their responses, we rank and compare the 12 behaviours with those from

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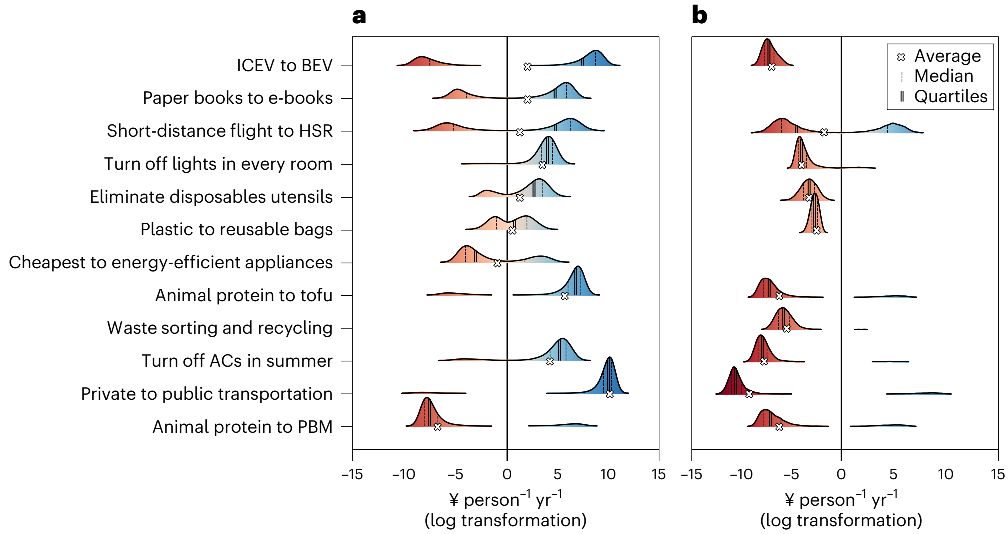

Fig. 2 | Distribution of pecuniary and non-pecuniary welfare changes. a,**b**, Kernel density plots of individual pecuniary net benefit (**a**) and non-pecuniary net benefit (**b**) across 12 demand-side mitigation behaviours as obtained from 10,000 simulations of randomly drawn parameters. The horizontal axis is log-transformed welfare change. Vertical double lines and dashed lines indicate the 25th and 75th percentiles and the median of welfare changes, respectively. Crosses indicate the average of welfare changes.

CBA (Supplementary Sections 3 and 4). The correlation coefficients for pecuniary and non-pecuniary costs are high, at 0.83 and 0.85, respectively. This survey, therefore, partly verifies that our methodological approach reflects the actual trade-offs residents face.

We also compute each behaviour's abatement cost by dividing individual welfare by emissions reduction. Most behaviours have large abatement costs, ranging from ¥778 to over ¥24,000 per tCO_2e (Table 2). For comparison, the CO_2 price in China's national emissions trading scheme is approximately ¥90 t^{-1}. These findings underscore the challenges of relying on demand-side mitigation as such strategies are not only often welfare-depreciating for individuals but also cost-ineffective. Consequently, policymakers require precise advice on which behaviours to target.

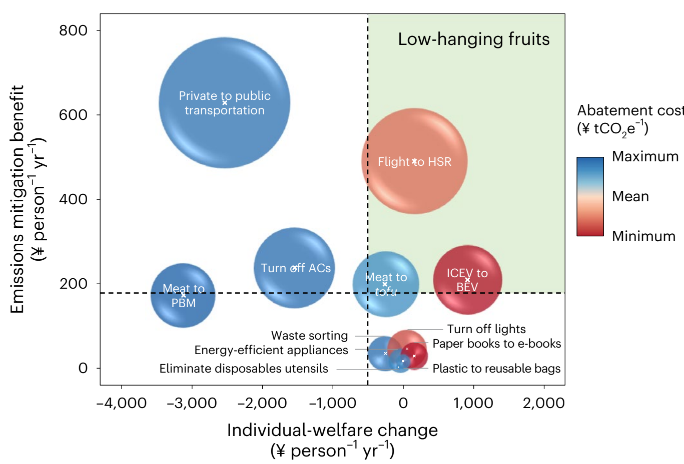

Fig. 3 | Individual- and social-welfare changes of climate mitigation behaviours. The horizontal axis represents individual-welfare changes (net benefit) from behavioural shift; the vertical axis represents social benefit from behavioural shift. Each bubble represents a demand-side mitigation behaviour. The size of the bubble indicates emissions mitigation potential; the bubble colour indicates the abatement cost of each behaviour; the crosses indicate the exact welfare changes. The vertical and horizontal dotted lines represent the average of individual and social-welfare changes across 12 behaviours.

Key opportunities in demand-side mitigation

To aid decision-makers, we use four metrics to represent the diverse objectives of different stakeholders: (1) social welfare, (2) individual welfare, (3) abatement costs and (4) emissions mitigation potential. Three behaviours exhibit above-average welfare gains at both the societal and individual levels, coupled with low abatement costs (Fig. 3). We term these the 'low-hanging fruits' where policymakers should concentrate efforts since incentives are aligned for all. Policymakers may also want to prioritize behaviours with large mitigation potential, such as private to public transport.

However, targeting behaviours does not automatically provide insights into effective policy levers. We undertake tornado analyses to identify the key drivers behind individual-welfare changes for the four selected behaviours: (1) internal combustion engine vehicle (ICEV) to battery electric vehicle (BEV), (2) animal protein to tofu, (3) flights to high-speed rail and (4) private to public transport (Fig. 4).

First, for ICEV to BEV, vehicle costs have the largest impact, and policies that widen the price gap between these two automobile types play a crucial role in promoting behavioural change. Surprisingly, electricity and gasoline prices, which are tightly regulated in Beijing, are less impactful, leaving little room for policymakers to utilize them. The results also suggest targeting ICEV owners with shorter commutes, as those with longer commutes are already incentivized to switch.

Second, meat to tofu involves few parameters due to the simplicity of this behaviour. Its welfare is dominated by psychological costs of dietary change (for example, disgust, loss of appetite). Although meat's price is more influential than tofu's, it is still less effective than addressing psychological barriers. Thus, carbon label policies might be more impactful than meat tax in encouraging low-carbon diets[33].

Third, short-distance flights to HSR is another low-hanging fruit. This behaviour is unique to China due to its extensive HSR network. The relative ticket prices of flights and HSR are crucial in determining welfare changes. Moreover, as travel time on HSR increases, this switch is less appealing, suggesting that travellers prefer flights for longer distances. Thus, flight taxes and distance-based subsidies for HSR tickets could encourage climate-friendly choices.

Last, while switching from private to public transport substantially reduces individual welfare, its mitigation potential may justify

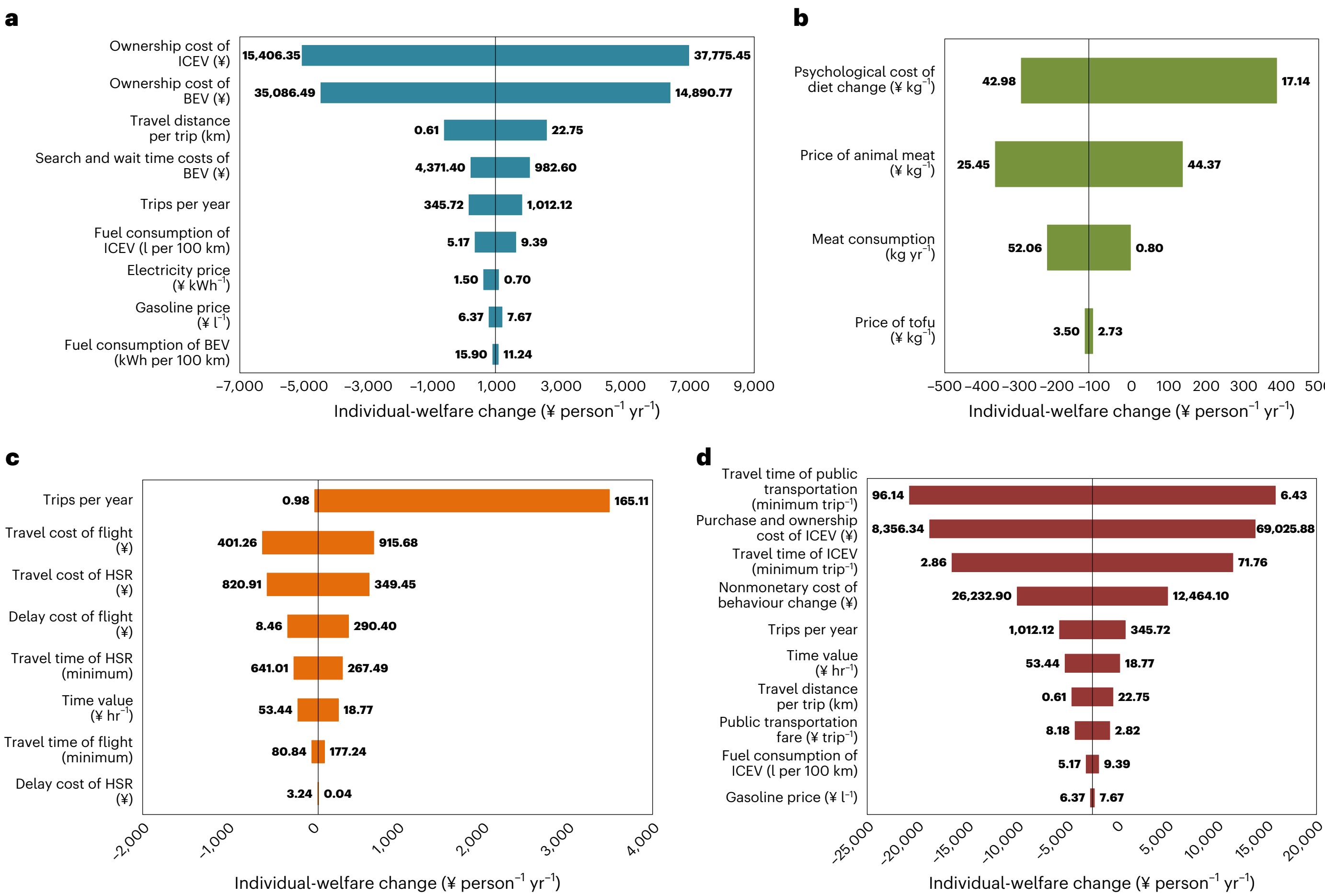

Fig. 4 | Tornado analyses of individual-welfare changes. a–**d**, Tornado, or one-way sensitivity analyses, of welfare changes for demand-side mitigation behaviours: ICEV to BEV (**a**), animal protein to tofu (**b**), short-distance flight to HSR (**c**) and private to public transportation (**d**). The numbers on either side of the bar are the 10th percentile and 90th percentile of each parameter on the vertical axis. The central vertical line dividing the bars indicates the average individual-welfare change.

policy actions. Tornado analyses show that travel time on public transport is an important factor. Non-monetary costs of public transport (for example, walking distance, overall discomfort) are also influential in affecting well-being, suggesting the need for targeted investments, such as sheltered walkways and gender-specific cabins[34,35]. Contrary to intuition, transport fares do not heavily affect welfare.

Discussion and conclusions

As the world faces increasing pressure to rapidly decrease GHG emissions, policymakers are turning to a broader mix of strategies[36]. One feasible approach is demand-side mitigation, which is estimated to reduce end-use-sector emissions by 40–70% while improving well-being[3,4]. However, a key knowledge gap in pursuing demand-side mitigation is having a complete picture of the trade-offs individuals face. We fill this gap by conducting a CBA of 12 commonly advocated climate-friendly behaviours from the perspective of Beijing residents.

We discovered these behaviours deliver mostly welfare losses, at both individual and societal levels. Further analysis revealed that non-pecuniary costs, such as psychological and time costs, are major reasons for welfare losses.

However, the average change in welfare is obscured by substantial variance. For example, although the average individual-welfare loss of private to public transportation is ¥2,449 person^{-1} yr^{-1}, approximately 45% of trials show gains. This variability suggests the potential to selectively incorporate demand-side behaviours. On the basis of individual and social welfare, individual abatement costs and mitigation potential, we recommend four behaviours for Beijing government: (1) ICEVs to BEVs, (2) animal protein to tofu, (3) flights to HSR and (4) private to public transport.

Finally, the complexity of factors governing each behaviour can challenge policymakers in formulating precise strategies. To address this, we employ tornado analysis to determine which factors are most influential. Our findings deliver multiple insights; for example, energy prices are not main factors driving the switch from ICEVs to BEVs. Instead, vehicle pricing plays a more decisive role, as supported by evidence from studies on electric-vehicle adoption[37–40].

In this regard, our findings deliver the following policy and research implications.

First, although demand-side mitigation is gaining traction in global discussions[41], projections are not always consistent with reality. For example, despite the proven welfare benefits of shifting to public transport[6], the share of public transport usage remains below 50% in most cities[42]. We attempt to reconcile these inconsistencies with a CBA of demand-side mitigation behaviours where we consider both pecuniary and non-pecuniary costs. Future work advocating demand-side mitigation may also want to include the full menu of trade-offs that individuals face.

Second, by focusing on Beijing, our findings are generalizable to major cities in China and applicable to metropolises worldwide. Importantly, we demonstrate that context greatly influences the selection of behaviours and policy options[27]. For example, animal protein to tofu is the only behaviour that enhances social welfare after accounting for emissions mitigation, primarily because tofu is a familiar and widely consumed protein in China[43]. The key takeaway here is that context is an important consideration when analysing demand-side mitigation, and in this regard, city- and region-level analyses are perhaps more useful than worldwide averages.

Third, we conduct the CBA primarily from the individual's perspective. Although this seems restrictive, it aligns with well-established principles that public goods are often overlooked by individual decision-makers[44]. Our findings serve as a 'stress test' on the viability of demand-side mitigation for private citizens. In turn, they provide a lower bound for government support required to promote such behaviours. In addition, by incorporating the benefits of emissions mitigation, we derive a corresponding upper bound. To further aid decision-making, we calculate the minimum SCC for all demand-side behaviours to at least not reduce welfare at a societal level (US$3,460 tCO_2e^{-1}). Overall, these parameters derived from our framework can enhance decisions regarding emissions mitigation on several fronts.

Fourth, our findings also yield a policy-relevant metric of abatement costs. Given the ongoing scarcity of climate finance, the world continually seeks cost-effective mitigation solutions. In this Article, we present the individual equivalent of GHG abatement costs and provide usable metrics for governments to design carbon pricing strategies to encourage pro-climate behaviours.

While we strive to be comprehensive, this study has limitations that future work can address. First, we do not account for rebound effects. For example, while a limited number of studies indicate that mileage increases after switching to energy-efficient gasoline vehicles[45], these responses are not well documented in electric vehicles. As more evidence gathers, future work can incorporate rebound effects. Second, our parameters, representing the average resident, may not reflect the variation by SES. For example, higher-income residents probably have a higher time cost. A viable extension is to explore how welfare changes arising from demand-side mitigation correlate with residents' SES. Third, by using a Likert scale, the survey only partially verifies our CBA findings. Future work can implement a comprehensive survey to audit each cost component of behavioural change.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-024-02146-4.

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Methods

CBA

Our framework compares the costs and benefits of climate-friendly behaviours with status quo.

To identify the set of behaviours, we first list pro-climate behaviours from advisories issued by the Beijing government (Supplementary Section 5). This yields 25 distinct behaviours that are ranked according to advocated frequency. To ensure generalizability across urban China, we supplement this list with behaviours advocated elsewhere. Using a similar approach, we confirm that the top 12 advocated behaviours across both lists are identical.

These 12 behaviours span four major end-use sectors—transportation, energy, diet and lifestyle (Table 1). As each can have countless permutations—switching from private to public transportation can vary in frequency (for example, one-quarter of the time)—we opt for complete changes for a clearer analysis.

Second, in listing the costs and benefits of each behaviour, we consider primarily the individual, which means that any publicly incurred costs or benefits, such as GHG emissions or social cohesion, are not included (Table 1). This stringent but realistic assumption is because public costs or benefits are generally not internalized by the user[46]. The individual-level costs and benefits across the 12 behaviours can generally be categorized as (1) purchase or operating, (2) comfort, (3) attention and (4) time (Supplementary Sections 6–17).

Third, we also evaluate emission mitigation potential. We first postulate that activity levels remain constant before and after behavioural changes. Subsequently, we obtain emissions factors from existing literature to compute the CO_2e emissions savings for each behaviour. The 12 behaviours have a substantial impact on emissions as per capita emissions will reduce by 30–40% (Supplementary Section 5) if all are adopted[47].

Location setting

We conduct this study in Beijing's context for several reasons. First, China is the world's top GHG emitter, and Beijing's per capita emissions of 3.2 tCO_2 ranked fourth provincially[47]. Second, Beijing shares similar characteristics with top-tier cities across China (Supplementary Section 5) and metropolises around the world where economic activities are dominated by consumption and service industries[48,49]. As such, demand-side mitigation has outsized impact here. Third, due to outsized household consumption, there are already multiple efforts organized by the local government to reduce demand-side emissions. For example, the Beijing government recently enabled residents to track their CO_2 emissions.

Monte Carlo simulation

To the extent that average welfare change provides broad overview, it obscures substantial heterogeneity in prices, preferences and societal conditions. To accommodate the range of values each parameter can take, we implement Monte Carlo simulations to capture the distribution of individual-welfare changes. For each behaviour, we select a random value for every parameter on the basis of their statistical distributions (Supplementary Sections 2 and 18). We then compute welfare change using one set of randomly selected parameters and repeat this process 10,000 times, yielding a full distribution.

Tornado analysis

As we rely on around seven parameters to compute each welfare change, we undertake a third analysis to quantify their individual influence. For each behavioural change, we select the 10th and 90th percentile values of one parameter and compute two values of individual-welfare change based on them, alongside the average values of all other parameters. We proceed to the next parameter in the same fashion. Overall, this stress test enables us to compare the ranges of welfare changes induced by each parameter. Intuitively, parameters that induce the largest range in welfare changes are deemed to have substantial impact.

Dataset

We rely on three sources for parameters: (1) existing studies, (2) statistical yearbooks and market studies and (3) directly computed statistics.

For (1), we use primarily studies conducted in Beijing or similar parts of China. In three instances where the parameter is from outside China but is still relevant to our calculations (for example, psychological costs of taking public transportation), we adapt these figures to Beijing's context by using an adjusted unit value transfer method widely used in the literature[50–53]. This method assumes the value to be transferred is a function of income and the elasticity of income with respect to willingness to pay (Supplementary Sections 2 and 18).

For (2), various stakeholders provide readily usable statistics. These parameters, directly collected from Beijing's residents, are considered representative of the city.

For (3), several parameters are computed directly by us. For example, we use city-by-year automobile sales data to compute statistics on car prices and fuel economy[54].

Last, to ensure the parameters have sufficient variation, we obtain from multiple sources such that each has an average of 5.5 sources from which we derive a statistical distribution using preset rules (Supplementary Section 2).

Data availability

All data generated or analysed during this study are included in this published article. Primary and secondary data supporting the findings of this study were all publicly available at the time of submission[55].

Code availability

All analyses were conducted using Microsoft Excel and Oracle Crystal Ball.

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Author contributions

J.-S.T.-S. conceived the study and coordinated the overall research. J.-S.T.-S., P.Q., and Y.Q. designed the research. Y.Q. performed the analysis with support from J.-S.T.-S., P.Q., J.L. and X.W. on analytical approaches and visualization. J.L. and P.Q. implemented the survey. J.-S.T.-S., and Y.Q. wrote the initial paper. J.-S.T.-S., P.Q., Y.Q. and J.L. contributed to subsequent revisions.

Competing interests

The authors declare no competing interests.

Additional information

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