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Quantifying the potential for climate change mitigation of consumption options

To cite this article before publication: Diana Ivanova *et al* 2020 *Environ. Res. Lett.* in press <https://doi.org/10.1088/1748-9326/ab8589>

Manuscript version: Accepted Manuscript

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1 **Review of reviews**

2 **“Focus on demand-side solutions for transitioning to low-carbon societies”**

3 **Quantifying the potential for climate change mitigation of consumption options**

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11 **Abstract**

12 **Background**

13 Around two-thirds of global GHG emissions are directly and indirectly linked to household
14 consumption, with a global average of about 6 tCO₂eq/cap. The average per capita carbon footprint of
15 North America and Europe amount to 13.4 and 7.5 tCO₂eq/cap, respectively, while that of Africa and
16 the Middle East - to 1.7 tCO₂eq/cap on average. Changes in consumption patterns to low-carbon
17 alternatives therefore present a great and urgently required potential for emission reductions. In this
18 paper, we synthesize emission mitigation potentials across the consumption domains of food, housing,
19 transport and other consumption.

20 **Methods**

21 We systematically screened 6,990 records in the Web of Science Core Collections and Scopus. Searches
22 were restricted to 1) reviews of lifecycle assessment studies and 2) multiregional input-output studies of
23 household consumption, published after 2011 in English. We selected against pre-determined eligibility
24 criteria and quantitatively synthesized findings from 53 studies in a meta-review. We identified 771
25 original options, which we summarized and presented in 61 consumption options with a positive
26 mitigation potential. We used a fixed-effects model to explore the role of contextual factors
27 (geographical, technical and socio-demographic factors) for the outcome variable (mitigation potential
28 per capita) within consumption options.

29 **Results and discussion**

30 We establish consumption options with a high mitigation potential measured in tons of CO₂eq/capita/yr.
31 For transport, the options with the highest mitigation potential include living car-free, shifting to a
32 battery electric vehicle, and reducing flying by a long return flight with a median reduction potential of
33 more than 1.7 tCO₂eq/cap. In the context of food, the highest carbon savings come from dietary changes,
34 particularly an adoption of vegan diet with an average and median mitigation potential of 0.9 and 0.8
35 tCO₂eq/cap, respectively. Shifting to renewable electricity and refurbishment and renovation are the
36 options with the highest mitigation potential in the housing domain, with medians at 1.6 and 0.9
37 tCO₂eq/cap, respectively. We find that the top 10 consumption options together yield an average
38 mitigation potential of 9.2 tCO₂eq/cap, indicating substantial contributions towards achieving the 1.5-
39 2°C target, particularly in high-income context.

1 Background

2 The need for demand reductions

3 Global greenhouse gas (GHG) emissions (carbon footprints) have been steadily rising, with faster,
4 sizable and immediate CO₂ emissions declines needed to limit cumulative emissions and reach net zero
5 emissions in 2050¹. Annual GHG emissions must decrease by 45% percent of their 2010-levels by 2030,
6 and reach net-zero by 2050 to limit temperature changes to 1.5°C above preindustrial levels. The
7 potential impacts and risks are substantially lower for a 1.5°C global warming compared with a 2°C,
8 including climate-related risks and threats regarding various ecosystems and human welfare¹. Global
9 GHG emissions amounted to 6.3 tCO₂eq/cap in 2011²; however, these are highly unequally distributed
10 across income groups and countries³⁻⁸. For example, the average per capita carbon footprint of North
11 America and Europe amount to 13.4 and 7.5 tCO₂eq/cap, respectively, while that of Africa and the
12 Middle East - to 1.7 tCO₂eq/cap on average (SM figure 1). For a population of 8.5 billion by 2030⁹,
13 emissions need to decrease to an average of ~2.8 tCO₂eq/cap by 2030, to comply with a pathway of
14 limiting climate change to 1.5°C of global warming. This is broadly in line with other estimates of per
15 capita carbon budgets¹⁰⁻¹².

16 The exact carbon budget for limiting global warming to 1.5°C is influenced by uncertainty about earth
17 system dynamics, as well as the scale and speed of adoption of negative emission technologies. Almost
18 all of the IPCC scenarios currently assume large-scale adoption of negative emission technologies at
19 massive scales¹³⁻¹⁵, which are potentially associated with strong adverse economic and environmental
20 consequences¹⁶, energy constraints (e.g. expanding carbon)¹⁷ and moral hazards because they tempt
21 policy makers to delay mitigation action now¹⁵.

22 Energy end-use is the least efficient part of the global energy system with the largest improvement
23 potential, where appropriate scaling down of the global energy demand allows for feasible de-
24 carbonization without betting on controversial negative emission technologies or geoengineering. While
25 technological solutions that decarbonize energy supply or capture carbon have to make a significant
26 mitigation contribution, changing consumption offers more flexibility for reducing carbon intensity in
27 the energy supply sector and limit the related supply-side risks¹⁸. Mitigation scenarios relying more
28 heavily on reduction in the demand of energy services are clearly associated with the lowest mitigation
29 and adaptation challenges^{15,19} and provide a range of co-benefits.

30 Challenging consumption

31 Behavior, everyday life and cultural norms around consumption have a crucial influence on energy use
32 and embodied emissions, with a high mitigation potential in various consumption domains^{18,20,21}. 65%
33 of global GHG emissions, and 50-80% of land, water and material use, can be directly and indirectly
34 linked to household consumption³. Income is a major driver of household carbon footprints^{5,7,8,22,23},
35 directly affecting purchasing power of households. Changes in household consumption patterns to low-
36 carbon alternatives, such as transport model shifts, home energy reduction and dietary shifts, thus
37 present a great mitigation potential.

38 Importantly, in the last decade, so-called multiregional input-output models (MRIO) have enabled the
39 systematic analysis of global production and consumption using consistent accounts of global GHG
40 emissions, and taking into account the scale and complexity of international trade and supply chains²⁴⁻
41 ²⁶. Consumption estimates derived through MRIOs were the first to fully allocate global emissions to
42 national household consumption (as well as government activities and investments) without double-
43 counting or omitting emissions, thus overcoming a long-standing limitation of single-regional input-
44 output approaches and lifecycle assessment (LCA) studies^{27,28}. However, understanding options for
45 change also requires bottom-up detailed information and insights going down to the product-level –
46 which is a challenge for MRIOs as they offer a quite limited product detail. In this context, LCAs are
47 relevant due to their process-specific and highly detailed nature. Here we argue that a combination of

1 bottom-up and top-down approaches provides a robust base for the review of the mitigation potentials
2 of consumption options.

3 In this paper, we systematically review the literature on mitigation potentials across various consumption
4 domains, including food, housing, and transport, focusing on academic publications since 2011 to ensure
5 relevance of derived estimates. While prior studies address some of these concerns (for a non-
6 comprehensive list of studies see ^{11,16,29-31}), we conduct meta-review including the more recent evidence.
7 Therefore, we provide a richer and more updated evidence base to inform about mitigation potentials of
8 changes in consumption practices, policies and infrastructure.

9 For the purpose of this paper, we do not capture mitigation potential associated with other avenues
10 towards social change²¹, such as community action and engagement^{32,33}, policies and incentives, political
11 engagement and non-violent civil disobedience³⁴ or reductions in overall working time and re-
12 definitions of paid labour²³, which all are highly relevant for challenging societal norms around
13 consumption and tackling climate change. Supply chain actors play a key role for climate change
14 mitigation, having direct agency over the majority of energy and emissions along supply chains^{35,36}.
15 Similarly, structural change by governments, ending fossil-fuel support, and providing low-carbon
16 infrastructures, is crucial to enable climate change mitigation³⁷⁻³⁹. We also do not review system-wide
17 effects and potential for income rebound effects⁴⁰⁻⁴². Our focus on consumption options should not be
18 interpreted as passing the mitigation responsibility to consumers⁴³. Still, a change in consumption
19 practices is needed for reaching net-zero carbon emissions^{1,44}.

20 **Research questions**

21 *Primary question: What is the mitigation potential of household-level consumption options within*
22 *mobility, housing and food sectors, when considering GHG emissions along the whole lifecycle?*

23 The primary question consists of the following question components:

24 *Population (P):* Household consumption of food, mobility and housing

25 *Intervention (I):* Consumption options within each end-use sector

26 *Comparator (C):* Average per capita carbon footprints of food, mobility and housing

27 *Outcome (O):* Annual carbon savings measured in per capita CO₂-equivalent reductions

28 *Study types:* LCA review studies with quantitative synthesis of data, MRIO studies of
29 household consumption, consumption scenario studies

30 We focus on household consumption associated with the three end-use sectors of food, transport and
31 housing as they are highly relevant in terms of consumption-based GHG emissions^{3,45}, energy⁴⁶ and
32 other resource use³ with some of the highest potential for consumption intervention^{29,47}.

33 *Secondary question: What factors may explain differences in carbon savings associated with each*
34 *consumption option across studies and contexts?*

35 We aim to capture sources of heterogeneity across studies, including system boundary⁴⁸, methodological
36 specificities, socio-economic, urban-rural and geographical context among others.

37 **Methods and search results**

38 The review followed the Collaboration for Environmental Evidence Guidelines⁴⁹ and it conformed to
39 ROSES reporting standards⁵⁰. It was conducted according to peer-reviewed protocol⁵¹ that was
40 submitted to Environmental Research Letters in March 2019 and approved in April 2019. The approved
41 protocol is openly available online⁵¹.

42 *Deviations from the protocol (outline)*

The following changes were made from the final published protocol⁵¹: first, we applied machine learning in the article screening process; second, we discussed the variation among studies in a qualitative manner in text rather than using the CEESAT tool for critical assessment (which was not suitable to assess non-review studies).

Searches for literature

Searches were performed on Web of Science Core Collections (WoSCC) and Scopus to identify relevant peer-reviewed studies published after 2011, using the University of Leeds subscription. The searches were done on titles, keywords and abstracts in English.

The search string was composed of three sub-strings: the *GHG emission* (X), *study type* (review) (Y) and *consumption domain* (Z) sub-string (Table 1). The sub-strings were connected with the Boolean operator “AND” as follows: X AND Y AND Z. We based the *GHG emission* sub-string (X) on prior similar searches^{52,53}. The *consumption domain* sub-string (Z) captured the consumption domains of transport, food, housing and other consumption (general), and specific consumption options (interventions) within these domains. The sub-strings in each domain-specific cell were connected with Boolean operator “OR” to form the *consumption domain* sub-string (Z). To test comprehensiveness of the search, we used a list of benchmark papers (see the protocol for details).

Sub-string X	GHG emission	((atmospheric OR anthropogenic OR effect* OR emission* OR footprint* OR mitigat* OR sav* OR reduc* OR budget* OR impact* OR decreas*) AND (carbon OR CO2 OR CH4 OR methane OR N2O OR nitrous oxide OR “greenhouse gas*” OR GHG OR GHGs)) OR (climat* AND (action* OR chang* OR warm* OR shift*)) OR “global warming” OR “emission reduction*” OR (mitigation AND (action* OR potential*)) NOT (catalyst* OR distill* OR chemicals OR super-critical OR foaming OR pore OR nanotube*))			
Sub-string Y	Study type	((lifecycle OR life-cycle OR “life cycle” OR LCA OR embodied OR indirect OR embedded OR “supply chain” OR “impact assessment*”) AND (review* OR meta-aggrega* OR meta-analys* OR metaggrega* OR metaanalys* OR meta-stud* OR metastud* OR overview* OR “systematic map” OR synthesis OR (meta AND (stud* OR analys* OR aggrega*))) OR (((multiregional OR multi-regional OR “multi regional”) AND (input-output OR “input output”)) OR MRIO))			
Sub-string Z-term	Consumption domains	(1) General	(2) Transport	(3) Food	(4) Housing
		(consum* OR lifestyle* OR demand* OR waste*)	((airplane* OR automobile* OR bicycl* OR bik* OR bus* OR car* OR commut* OR cycl* OR *diesel OR driv* OR engine* OR flight* OR fly* OR fuel* OR gasoline OR “liquefied petroleum gas” OR LPG OR kerosene OR metro OR mobil* OR plane* OR ride* OR subway OR touris* OR train* OR transit OR transport* OR travel* OR underground OR vehicle*))	(beef OR beverage* OR “calor* intake” OR cereal* OR cheese OR chicken OR dairy OR diet* OR egg* OR fertilizer* OR fish OR food OR fruit* OR grain* OR meat OR milk OR plant* OR pork OR restaurant OR sugar OR vegetable* OR yoghurt)	(“air condition*” OR apartment* OR appliance* OR boiler* OR cement OR clay OR concrete OR construct* OR cool* OR dwelling* OR electronic* OR energy OR “floor space” OR heat* OR hemp OR home* OR hous* OR light* OR “living space” OR metal* OR refrig* OR rent* OR room OR sand OR shelter OR “solar panel*” OR stone OR timber OR window* OR “white good*” OR wood)

Consumption interventions	<i>(decreas* OR durab* OR eco* OR efficien* OR green* OR longevity OR natural OR maintain* OR recycl* OR reduc* OR renewabl* OR repair* OR reus* OR "second hand" OR second-hand OR shar* OR sufficien*)</i>	<i>("light weight" OR electric* OR hybrid* OR telecommut* OR telework* OR walk*)</i>	<i>("eat less" OR compost* OR flexitarian OR local OR organic OR season* OR vegan OR vegetarian)</i>	<i>(cohous* OR co-hous* OR downsize* OR insulat* OR refurbish* OR renovat* OR retrofit* OR ((temperature OR thermal) AND (preference OR comfort OR set-point* OR "set point*" OR setting)))</i>
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1 Table 1: A summary of the sub-string X, Y and Z terms. The sub-strings are shown as formatted for Web of Science search.
2 See the supplementary material for Scopus formatting.

3 A search on WoSCC (conducted on 24th May 2019) yielded 5,638 records and on Scopus additional
4 1,352 records (see the supplementary materials for search queries), totaling 6,990 records. The results
5 of both searches were combined into a "Scoping Review Helper" library where exact duplicates were
6 removed. Figure 1 provides more detailed overview of the search and screening process of the review.

7 Article screening and eligibility criteria

8 Article screening was done first at the title and abstract level, and then on full text level (Figure 1). The
9 title and abstract screening was supported by machine learning. Table 2 provides an overview the
10 eligibility criteria according to the PICO framework (see the supplementary information for more
11 details).

12 Having reviewed the first 991 records (15% of unique records) drawn randomly from the total number
13 of records, we started an iterative process where at each iteration, we 1) trained a machine learning
14 model with the already screened documents; 2) fitted this model on the unseen documents; and 3)
15 assigned the next set of documents for review by selecting the documents predicted to be most relevant.
16 We went through four iterations of machine learning prioritized screening, (see Figure 2.a) and each had
17 decreasing proportions of relevant documents in the set of reviewed records. The first iteration of 250
18 documents contained 38% of relevant records, while the last iteration of 100 documents - only 3%
19 relevant documents. We screened a final random sample of 100 documents, and used this sample to
20 generate an estimate of the number of relevant documents remaining using the Agresti-Coull confidence
21 interval. Figure 2.b) shows the minimum recall at different levels of uncertainty.

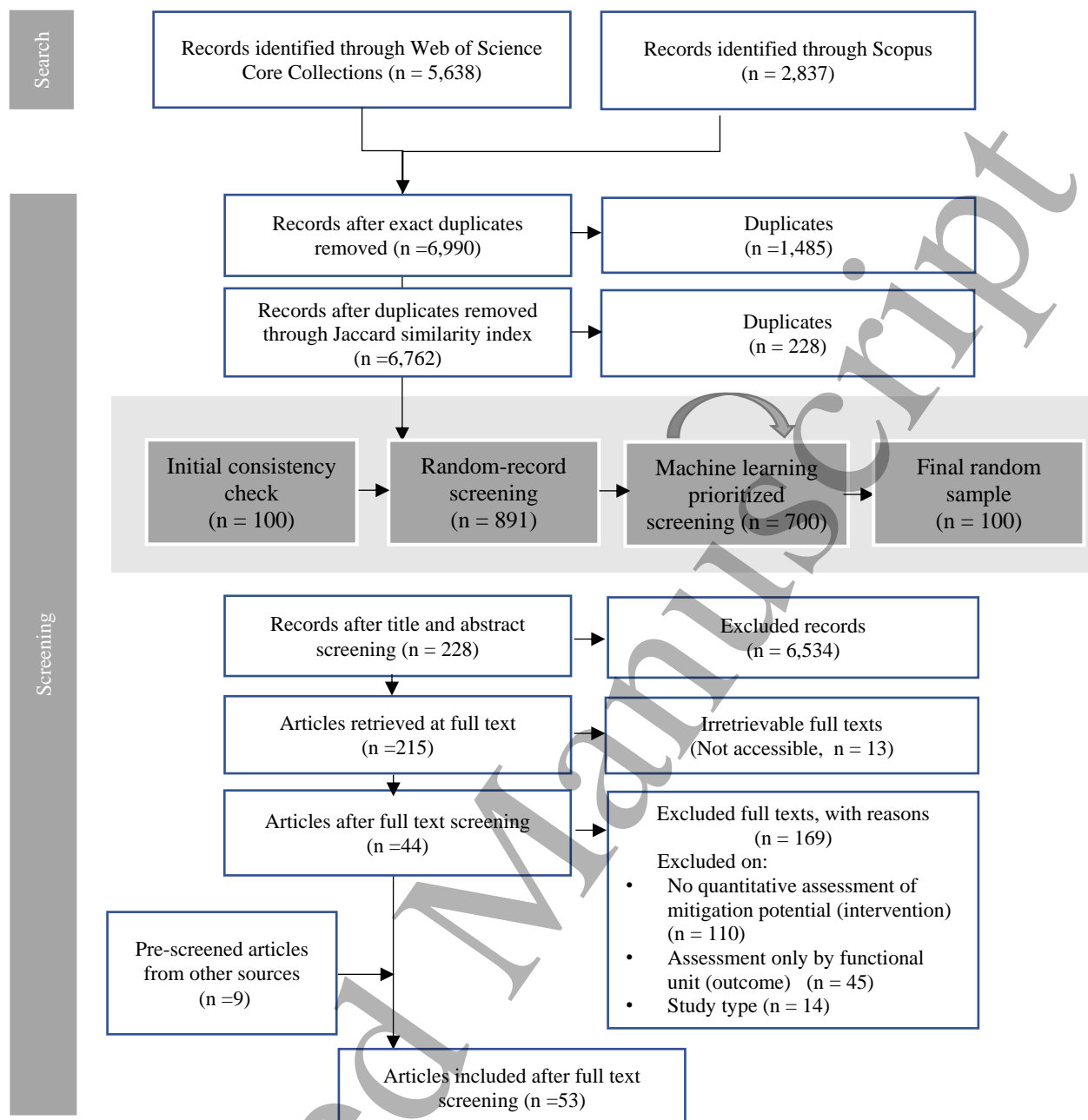


Figure 1: Flow diagram – adapted from the ROSES flow diagram for systematic reviews¹²⁸. See the supplementary data extraction for more detail about excluded articles and the supplementary materials for details on the methods.

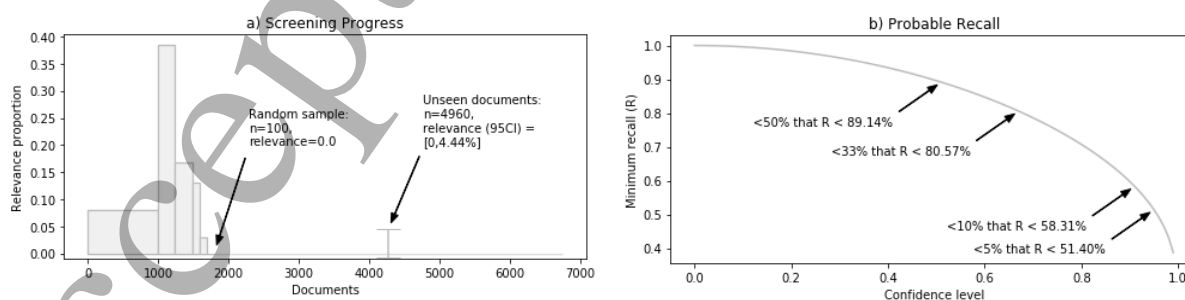


Figure 2: Screening progress (a) and probable recall (b). In a), each bar represents a set of screening decisions, with the width showing the number of documents and the height showing the percentage of them that was relevant. The first bar represents the 991 documents screened at random. The subsequent bars represent 4 sets of machine learning prioritised documents, a random sample of 100 documents, and remaining unseen documents. The random sample is used to generate the errorbar, the Agresti-Coull confidence interval. b) shows the probability distribution of the minimum level of recall, based on the assumption

	Inclusion criteria	Exclusion criteria
<i>Eligible population/ setting</i>	No geographical restriction and focus on household consumption	Mitigation potential not directly linked to households (e.g. government spending)
<i>Eligible intervention: Consumption options by consumption domain</i>	<ul style="list-style-type: none"> • Direct reduction –consumption reduction, shift between consumption categories, and curtailment. Examples include living car-free or avoiding flights (transport)²⁹, consuming fewer calories (food)⁵⁴ and conserve energy at home (housing)⁵⁵ • Indirect reduction –changes in consumption patterns, changes in use behavior and changes in disposal patterns. Examples include carpooling (transport), sharing of food surplus (food), or equipment maintenance (housing)⁵⁶ • Direct improvement –purchases of products that are more efficient in use or produced more efficiently. Examples include opting for electric vehicles (transport)⁵⁷, plant-based diet (food)^{29,54} and renewable energy (housing)²⁹. • Indirect improvement –changes in disposal behavior. Examples include recycling batteries (transport), food packaging (food), electrical appliances (housing). 	Mitigation options beyond the adopted framework ⁵⁸ were out of scope. This includes macro-economic or industrial energy efficiency measures and technological solutions, producer incentives or other options on the supply side; population ¹¹ measures; mitigation potential of policies
<i>Outcome: Mitigation potential and lifecycle emissions</i>	Mitigation potential assessed through annual carbon savings in kilograms/tons CO ₂ -equivalents per capita, converting GHGs (e.g. CO ₂ , CH ₄ , N ₂ O, SF ₆) to equivalent amounts of CO ₂ (e.g. GWP100).	Focus only on direct emissions ⁵⁶ (e.g. well-to-wheel LCAs) or carbon intensities in functional units with no estimate of consumption; system-wide effects and potential for income rebound effects ⁴⁰⁻⁴² . Consumption activities with high carbon intensity ^{3,59} should be considered to avoid rebound.
<i>Study types</i>	Supply chain lifecycle GHG emissions through LCA review studies and MRIO studies, physical trade flow or hybrid modelling studies, studies on re-designing of consumption.	Systematic maps and reviews with only narrative synthesis; mitigation assessment through regression coefficients.

1 Table 2: Eligibility criteria. See SI table 1 for more details on the inclusion and exclusion criteria.

2 After titles and abstract screening, we considered 228 relevant records at full-text (Figure 1). In addition,
 3 nine pre-screened articles were added separately, which were considered relevant but were not found
 4 through the original search. Six of these additions were not published at the time of the original search.
 5 We applied the inclusion and exclusion criteria (Table 2) and a final set of 53 articles were considered
 6 eligible at full text. See the supplementary materials and extraction sheet for more details on the
 7 procedure.

8 We used software for evidence synthesis “Scoping Review Helper” (developed by MCC Berlin), for
 9 managing search results, removing duplicates, screening records, extracting data and conducting
 10 synthesis. We also designed search queries through managing topics iteratively, and refined the
 11 inclusion criteria during the screening process.

12 Data extraction and synthesis

13 We extracted meta-data from each reviewed study, including title, author team, year of publication and
 14 data collection, consumption option and domain, geographical context, method, system boundary,
 15 carbon metric and GHGs included from the eligible studies. We further extracted the study quantitative
 16 findings, e.g. average, standard deviation, number of studies reviewed, min-max range, absolute and
 17 relative carbon savings, contextual carbon footprint calculations. Missing or unclear information was
 18 requested directly from authors. We recalculated the mitigation potential of consumption options in tons
 19 CO₂ equivalents per capita where needed in order to improve comparability across studies.

20 The baselines considered in the reviewed studies are associated with large uncertainties and different
 21 assumptions (e.g. average baseline vs high-carbon baseline). At the same time, the baselines are key for

1 the calculation of mitigation potentials and may largely affect the order of consumption options on the
 2 graph. In such cases results should be interpreted with caution.

3 *Data synthesis and potential effect modifiers/reasons for heterogeneity*

4 Included literature is characterized by a large variation in methods, internal validity of studies, coverage
 5 of different GHGs, location and timeframe, system boundary, assumptions about uptake rate⁵⁶ and other
 6 potential sources of heterogeneity. We discussed heterogeneity along with the narrative synthesis of
 7 study findings. Where data allowed, we considered the effect modifiers in quantitative synthesis. We
 8 used a fixed-effects model to explore the relationship between predictors (various geographical,
 9 technical and socio-demographic factors) and outcome variables (mitigation potential per capita) across
 10 consumption options as a way to explain the variation in mitigation potential. Using the fixed-effect
 11 approach, we control for factors invariant across mitigation options, which we could not include directly
 12 in our model.

13 **Review Results**

14 Figure 3-6 depict the mitigation potential ranges of various consumption options in the domains of food,
 15 transport, housing and other consumption. Positive values are associated with positive mitigation
 16 potential, with the options ordered by medians.

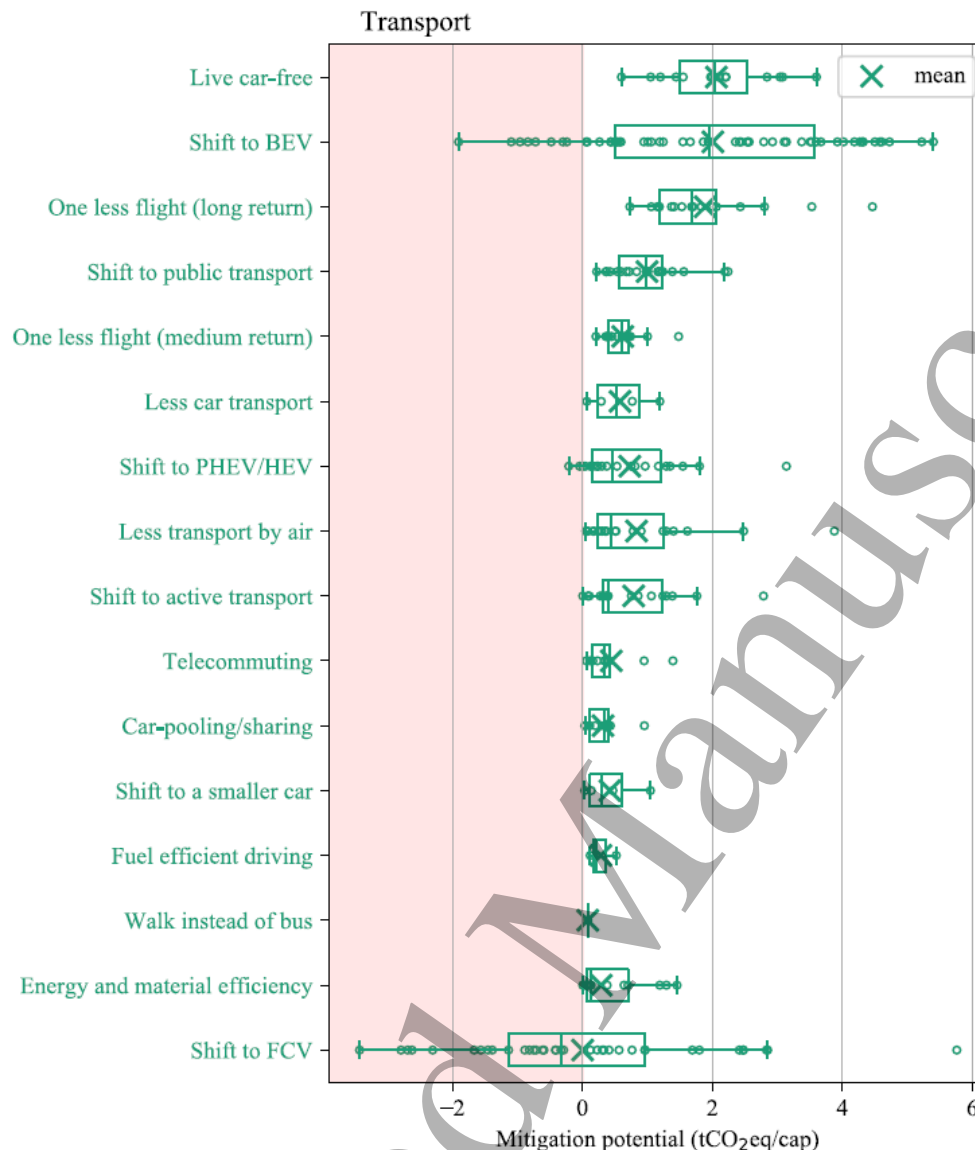
18 **Transport**

19 The highest mitigation potential of reviewed options is found in the domain of transport (Figure 3),
 20 which is also associated with a substantial carbon footprint in most world regions (SM figure 1). The
 21 consumption options with the highest mitigation potential advocate reduction in car and air travel, as
 22 well as a shift toward less carbon intensive fuel sources, means and modes of transportation.

23 There is substantial mitigation potential in reducing air travel for those who fly. *One less flight (long*
 24 *return)* may reduce between 4.5 and 0.7 (mean of 1.9) tCO₂eq/cap, while taking *One less flight (medium*
 25 *return)* – between 1.5 and 0.2 (0.6) tCO₂eq/cap. The two options have a median reduction potential of
 26 1.7 and 0.6 tCO₂eq/cap, respectively. Yet, the number of trips per passenger in 2018 amounted to 2.0 in
 27 the United States and to 3.6 and 4.8 in wealthy European countries such as Luxembourg and Norway,
 28 with the numbers projected to increase rapidly⁶⁰. Other studies exploring partial reductions in air travel
 29 (*Less transport by air*) find an average reduction potential of 0.8 tCO₂eq/cap. The overall mitigation
 30 potentials strongly depend on income, as high-income households fly much more^{4,5,61}.

31 Reducing car travel is associated with substantial mitigation potential. *Living car-free* has the highest
 32 median mitigation potential across all of the reviewed options at 2.0 tCO₂eq/cap, with a range between
 33 3.6 and 0.6 tCO₂eq/cap. Assumptions around vehicle and fuel characteristics as well as travel distance
 34 are key for the estimated mitigation potential, with the maximum value in our sample being associated
 35 with giving up an SUV²⁹. Partial car reductions, captured by the options of *Less car transport*, *Shift to*
 36 *active transport* and *Shift to public transport* in our sample, have an average mitigation potential
 37 between 0.6 and 1.0 tCO₂eq/cap. These options are generally limited to replacing short and urban car
 38 trips with alternative transportation modes or reducing leisure trips^{42,62–64}, which constitute a relatively
 39 small portion of all travel and its embodied emissions^{57,65,66}. Yet, active and public transport alternatives
 40 have much lower carbon intensities per travel km^{57,67,68}. Active and public transport are characterized
 41 by average carbon intensities at 0.00 and 0.09 kgCO₂eq/km, while individualized motorized transport at
 42 0.23 kgCO₂eq/km⁵⁷. *Telecommuting* practices reduce commute emissions between 1.4 and 0.1 (mean of
 43 0.4) tCO₂eq/cap, while *Car-pooling and car-sharing* and *Fuel efficient driving* have an average carbon
 44 savings of 0.3 tCO₂eq/cap. The practice of ride-hailing, or receiving transportation from an unlicensed
 45 taxi service, may result in an increase in emissions as a result of “deadheading”, the travelled miles
 46 without a passenger between hired rides⁶⁹. For example, a non-pooled ride-hailing trip generates 47%
 47 greater emissions per mile compared to a private car trip of an average fuel efficiency⁶⁹. The number of
 48 passenger sharing the trip makes a substantial difference in terms of mitigation potential, as well as the

1 type of trip that is displaced (e.g. private driving, public transit, walking). Thus, the shift from public
 2 transport to active transport⁴² offers only marginal mitigation potential per capita (Figure 3).



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Figure 3: Annual mitigation potential of consumption options for transport measured in tCO₂eq/cap. The figure is based on a sample of 23 review articles and 16 consumption options. Negative values (in the red area) represent the potential for backfire. The dots represent single reviewed studies and the x-s – the average mitigation potential within the same consumption option. The 25th percentile, median and 75th percentile are noted with lines, with the options ordered by medians. SI Data extraction sheet contains an overview of all options. For transport, we adopted the estimate of 15000 km per passenger per year in the OECD⁷⁰, 1000 km in China⁷¹ and 24000 km in the USA^{71,72} for studies which do not specify annual travel.

The differences in assumed travelled distance explain why options for reducing car travel altogether may show lower mitigation potential compared to a shift to alternatives of internal combustion engine vehicles (ICEV). The *Shift to battery electric vehicle (BEV)* from ICEV has mitigation potential between 5.4 and -1.9 tCO₂eq/cap, with an average and median of 2.0 tCO₂eq/cap. Carbon reduction potential varies between 3.1 and -0.2 (mean of 0.7) tCO₂eq/cap for (plug-in) hybrid electric vehicles (PHEV/HEV), and between 5.8 and - 3.4 (mean of 0) tCO₂eq/cap for fuel cell vehicles (FCV). The carbon intensity of the electricity mix (widely varying across countries⁷⁰) is crucial for the GWP of BEVs^{70,73–76}, where the electricity mix alone was found to explain almost 70% of the variability in LCA results⁷⁶. Furthermore, while modelling studies are often based on the average grid carbon intensity, the marginal emissions factor may be substantially higher if additional demand is met by fossil-fuel thermal plants^{70,76}, e.g. 35% higher in the UK⁷⁰. Fuel consumption is the most influential factor affecting the

1 GWP of ICEV, HEV and PHEV⁷⁴. PHEV have a similar electricity consumption to that of BEV when
2 driving electric⁷⁵. Strong coal-dependence (when the proportion of coal electricity is 20% or larger)⁷⁷
3 eliminates any potential GHG savings with the shift to FCV. The main advantage of a FCV compared
4 to a BEV is the higher range and quick refilling of the tank^{75,77}; yet, the necessary H₂ filling station
5 infrastructure is currently lacking⁷⁵. We noted substantial differences in the system boundary and
6 modelling approaches, which may also influence the mitigation ranges.

7 *Energy and material efficiency* (e.g. more efficient combustion engine, lightweight materials, improved
8 fuel economy, cleaner fuels)^{73,78–81} brings a reduction between 1.46 and 0.01 (mean of 0.3) tCO₂eq/cap.
9 Yet, there has been a clear trend of increased number of vehicles⁶⁴, travelled distance per person⁷⁰ and
10 increased mass of light-duty vehicles⁸⁰, which offset efficiency improvements with transport emissions
11 still on the rise⁶⁴. Differences in ranges may be explained by assumptions about recycling rates and
12 material substitution factors, vehicle lifetime, class and drive cycle and other factors^{78,80}.

13 We could not evaluate annual mitigation potential from biofuels, as most studies communicate
14 mitigation potential in terms of functional unit (e.g. per MJ of fuel), without further discussions of
15 travelled distance and vehicle efficiency. There are large uncertainties around the mitigation potentials
16 of biofuels due to inconsistencies in scope definition (e.g. system boundary and functional unit),
17 assumptions (e.g. impacts of infrastructure and coproduction), technological choices, and data sources⁸².
18 If system boundaries are expanded to include indirect LUC, physical land constraints from food and
19 feed, and biodiversity conservation as well as the temporal effects on natural carbon stocks, biofuels are
20 revealed as less attractive if not detrimental option for climate change mitigation^{83,84}.

21 Food

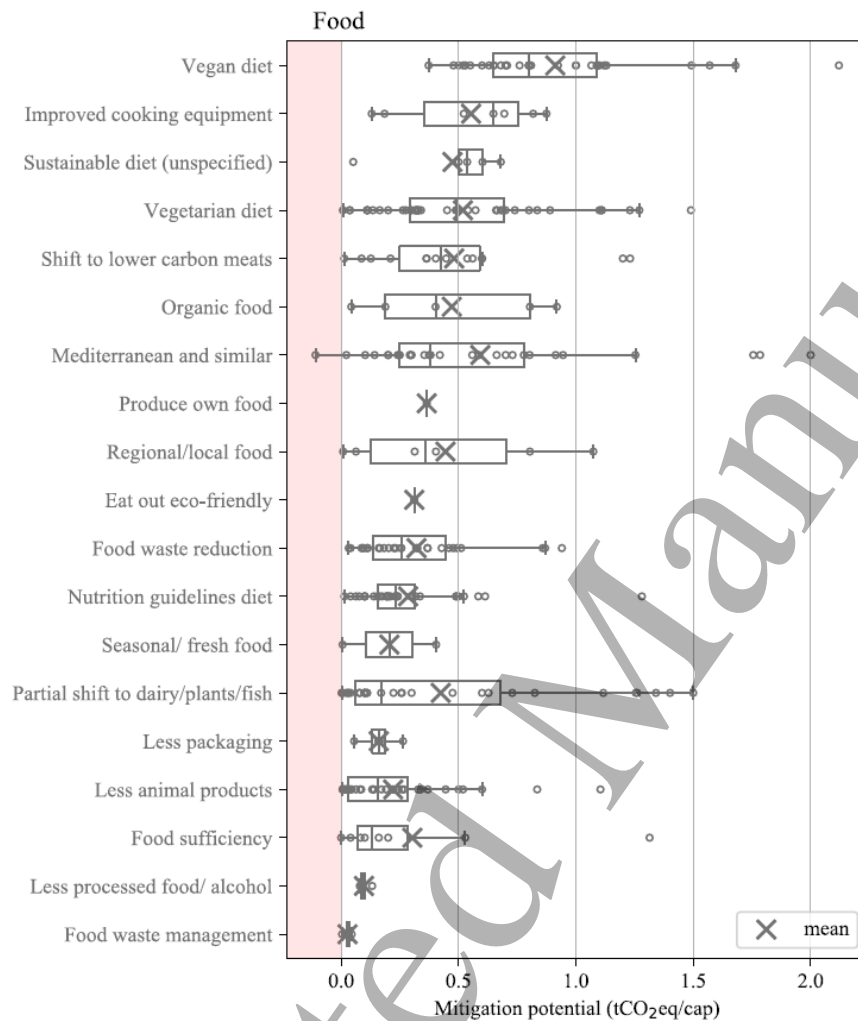
22 Figure 4 provides an overview of various consumption options in the food domain. The majority of
23 reviewed studies covered the potential GHG reduction associated with a change of diet and a reduction
24 in food waste.

25 The mitigation potential associated with a diet change involving a reduction in the amount of animal
26 products consumed varies between 2.1 and 0.4 tCO₂eq/cap (mean of 0.9 tCO₂eq/cap) for a *Vegan diet*,
27 between 1.5 and 0.01 (0.5) for a *Vegetarian diet*, and between 2.0 and -0.1 (0.6) for *Mediterranean and*
28 *similar diet* – e.g. Atlantic and New Nordic. The three types of diets have median mitigation potential
29 of 0.9, 0.5 and 0.4 tCO₂eq/cap, respectively. Adopting more *Sustainable diet* or a *Shift to lower carbon*
30 *meats* is also associated with sizable reductions, with an average annual reduction of 0.5 tCO₂eq/cap.
31 The carbon intensity per calorie/kg of primary product is substantially lower for vegetal foods compared
32 to ruminants, non-ruminants and dairy^{11,85–87}, with meat producing more emissions per unit of energy
33 due to energy losses at each trophic level⁸⁸. Emissions associated with land use change (LUC) are also
34 most significant for meat-intensive diets⁸⁹, due to increases in pasture land and arable land for growing
35 feed. *Nutrition guidelines diets* optimized with regards to health guidelines (generally including a
36 reduction in the red meat intake and increase in plant-based foods) are associated with more moderate
37 potential reductions between 1.3 and 0.01 tCO₂eq/cap (mean of 0.3 tCO₂eq/cap).

38 *Improved cooking equipment* is associated with strong mitigation potential amounting to a mean and a
39 median of 0.6 tCO₂eq/cap. Cooking methods, fuels, choice of food and cook-ware, use and management
40 of the cook-ware as well as storage time and space are all relevant factors^{90,91}.

41 Other options for carbon footprint reductions in the food domain focus on the production methods,
42 transportation, seasonality and processing of food products. *Organic food* have lower emissions
43 compared to conventionally produced food, with an average annual mitigation potential of 0.5
44 tCO₂eq/cap and a median of 0.4 tCO₂eq/cap. This mitigation potentials is primarily attributable to the
45 increased soil carbon storage and reductions of fertilizers and other agro-chemicals^{92–94}. Yet, increases
46 in GHG emissions from organic food for the same diet are not uncommon^{92,93,95}, due to lower crop and
47 livestock yields of organic agriculture and the potential increase in production and associated LUC⁹².
48 Opting for *Regional and local food* and *Seasonal and fresh food* involves average reductions of 0.4 and

1 0.2 tCO₂eq/cap. One of the advantages of producing and consuming food in its natural season is that it
 2 does not require high-energy input from artificial heating or lighting^{91,96}, thus reducing the embodied
 3 GHG emissions. Producing and consuming locally may reduce emissions from transportation and abate
 4 impact displacement overall⁹¹, provided there are not large increases in energy requirements (e.g. in the
 5 case of heated greenhouse production or through the use of fertilizer^{97,98}). Regional production requiring
 6 the use of heating systems (e.g. fresh vegetables in the beginning of the growing season) may be
 7 associated with higher emissions compared to even substantial long-distance transport emissions from
 8 production sites without heating⁹⁹.



9
 10 *Figure 4: Annual mitigation potential of consumption options for food measured in tCO₂eq/cap. The figure is based on a sample*
 11 *of 32 review articles and 19 consumption options. Negative values (in the red area) represent the potential for backfire. The*
 12 *dots represent single reviewed studies and the x-s – the average mitigation potential within the same consumption option. The*
 13 *25th percentile, median and 75th percentile are noted with lines, with the options ordered by medians. SI Data extraction sheet*
 14 *contains an overview of all options.*

15 We also note substantial mitigation potential associated with the reduction in consumed food and waste.
 16 *Food sufficiency* – implying a reduction in the overall food intake – and *Food waste reduction* options
 17 mitigate an average of 0.3 tCO₂eq/cap and a median of 0.1 tCO₂eq/cap. Food waste studies generally
 18 make a distinction between avoidable and potentially avoidable waste, which are said to amount to
 19 80%¹⁰⁰ of all food waste. *Food waste management* of unavoidable food waste is associated with more
 20 modest average mitigation potential of 0.03 tCO₂eq/cap.

21 There are large uncertainties^{92,101–104} associated with environmental (e.g. emissions arising from
 22 biological processes, LUC and highly integrated production such as beef and dairy), nutritional data
 23 (e.g. consumption and waste, weighting factors for gender and age). Impact assessment studies generally

do not consider emissions associated with LUC¹⁰¹, which is estimated to contribute between 9 and 33% of the total livestock emissions (primarily attributable to feed imports)^{92,101}. Furthermore, even though food is a basic good (see SM figure 2), the distribution of diets and their embodied GHG impacts is largely unequal¹⁰⁵. For example, 20% of diets with the highest carbon contribution in the USA account for more than 45% of the total food-related emissions, mostly linked to meat consumption¹⁰⁵.

Housing

The methodological differences were particularly strong for the reviewed studies in the housing domain, where mitigation potential was quantified per kWh of energy use, kg of primary material¹⁰⁶, embodied and operational energy per m² of living space, unit of fuel, thermal insulation per surface unit¹⁰⁷ and others.

The mitigation options with the highest potential on average include purchasing *Renewable electricity* and *Producing own renewable electricity* with average values of 1.5 (ranging between 2.5 and 0.3) and 1.3 (ranging between 4.8 and 0.1) tCO₂eq/cap (Figure 5). The two options have median mitigation potential of 1.6 and 0.6 tCO₂eq/cap, respectively. The mitigation potential of adopting renewable technologies is dependent on the energy source¹⁰⁸ and a wide range of contextual factors¹⁰⁹ – e.g. type of electricity to manufacture renewable technologies, location (affecting the amount of energy that can be produced in the use phase), and the way technologies are used and maintained¹⁰⁹.

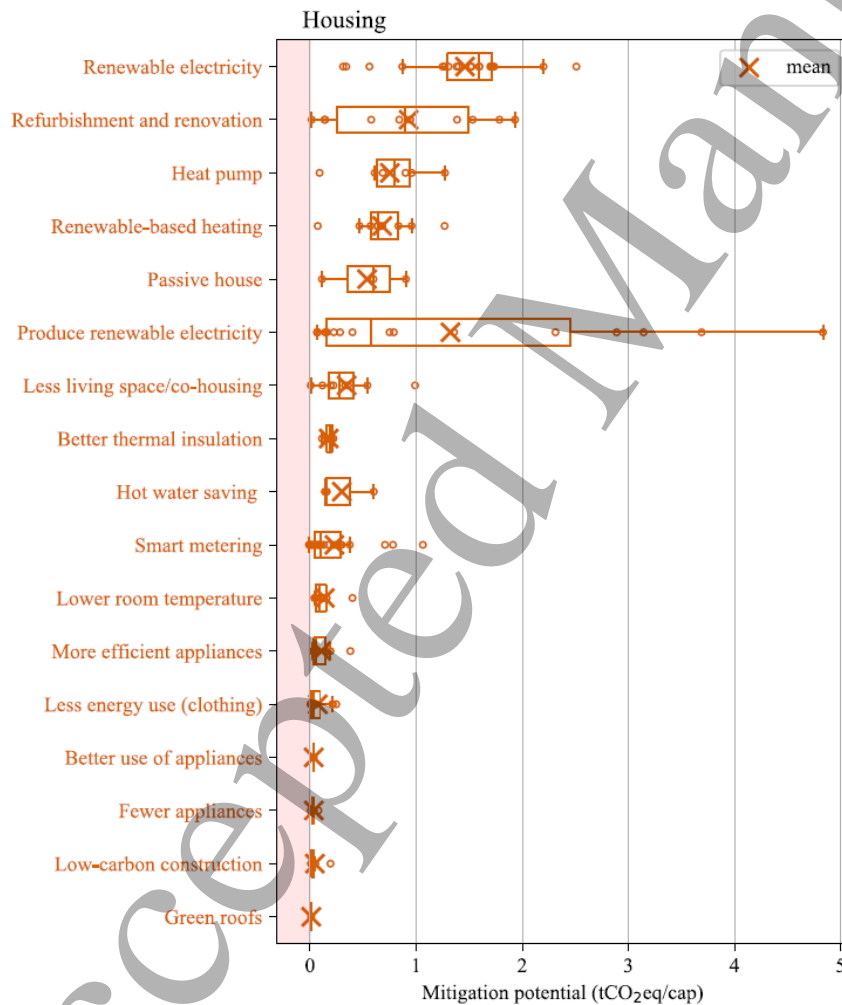


Figure 5: Annual mitigation potential of consumption options for housing measured in tCO₂eq/cap. The figure is based on a sample of 13 review articles and 17 consumption options. Negative values (in the red area) represent the potential for backfire. The dots represent single reviewed studies and the x-s – the average mitigation potential within the same consumption option (options ordered by averages). The 25th percentile, median and 75th percentile are noted with lines, with the options ordered by medians. SI Data extraction sheet contains an overview of all options.

1
2
3 1 Other effective infrastructure-related options associated with space heating include *Refurbishment and*
4 2 *renovation*, opting for *Heat pump* and *Renewable-based heating*, which offer an average mitigation
5 3 potential of 0.9, 0.8 and 0.7 tCO₂eq/cap, respectively. The shift to a *Passive house* is associated with an
6 4 average reduction potential of 0.5 tCO₂eq/cap (based on estimates by three studies), excluding GHG
7 5 emissions associated with changes in infrastructure. The carbon intensity of materials and sources^{62,108},
8 6 infrastructure⁶² and geographical differences in energy and heating requirements and temperature
9 7 tolerance⁵⁷ are all key factors for the absolute mitigation potential associated with these options. The
10 8 reviewed mitigation potential of *Smart metering* varies between 1.1 and 0 tCO₂eq/cap, with an average
11 9 of 0.2 tCO₂eq/cap. *Smart metering* improves household awareness of their energy consumption and
12 10 support energy reduction activities (e.g. it may encourage retrofitting of houses or change of appliances
13 11 and equipment)¹¹⁰. These indirect effects are generally not captured in pilot studies¹¹⁰. Factors such as
14 12 climate differences, dwelling type and share of renewables in the local grid are of crucial importance
15 13 for the carbon savings potential¹¹⁰.

16 14 *Less living space and co-housing* – which includes options such as smaller living space (and hence less
17 15 heating and construction), collective living with others and renting out guest rooms for other people to
18 16 live in – offer carbon reductions of up to 1.0 tCO₂eq/cap, and an average of 0.3 tCO₂eq/cap. When
19 17 people live together, they tend to share space heating, cooling, lighting and the structure of the common
20 18 living space, appliances, tools and equipment^{23,111,112}. While these estimates of household economies of
21 19 scale from shared living are only limited to the housing domains, sharing within households extends to
22 20 other types of consumption (e.g. sharing food and cooking together)¹¹². Furthermore, the energy use
23 21 reductions associated with an additional household member tend to be lower for large households
24 22 compared to small households¹¹². As building size is the most important factor for home energy
25 23 consumption, downsizing may substantially reduce housing-related emissions and energy use¹¹³.
26 24 However, there are significant structural (e.g. lack of adequate alternatives), psychological (e.g.
27 25 attachment) and security barriers (e.g. loss of ownership) related to downsizing¹¹³. Other behavioral
28 26 interventions such as *Hot water saving* and *Lowering room temperature* by 1-3°C bring about an average
29 27 saving of 0.3 and 0.1 tCO₂eq/cap, respectively.

30 28 Other consumption

31 29 Finally, other consumption options with substantial mitigation potential include not having a pet and
32 30 sharing and consumption of services instead of goods with median mitigation potential around 0.3
33 31 tCO₂eq/cap (Figure 6). The service/sharing economy includes options such as opting for local, non-
34 32 market and community services, share and repair. Strategies encouraging sharing include adequate
35 33 design and infrastructure for durability, recyclability, reuse and product longevity⁸¹ and incentives for
36 34 multi-household living⁵⁷, grassroots initiatives and downsizing^{32,114}. Yet, studies also warn that peer-to-
37 35 peer strategies do not necessarily translate into carbon footprint reductions due to extra income and
38 36 induced consumption¹¹⁵.

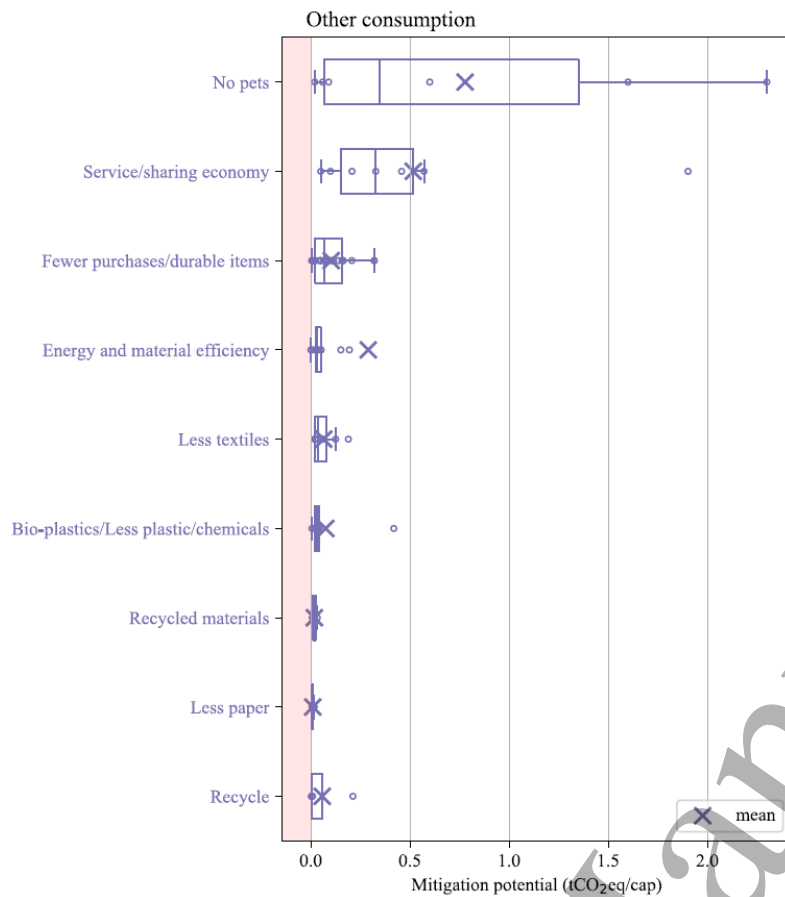


Figure 6: Annual mitigation potential of consumption options for other consumption measured in tCO₂eq/cap. The figure is based on a sample of 10 review articles and 9 consumption options. Negative values (in the red area) represent the potential for backfire. The dots represent single reviewed studies and the x-s – the average mitigation potential within the same consumption option (options ordered by averages). The 25th percentile, median and 75th percentile are noted with lines, with the options ordered by medians. SI Data extraction sheet contains an overview of all options.

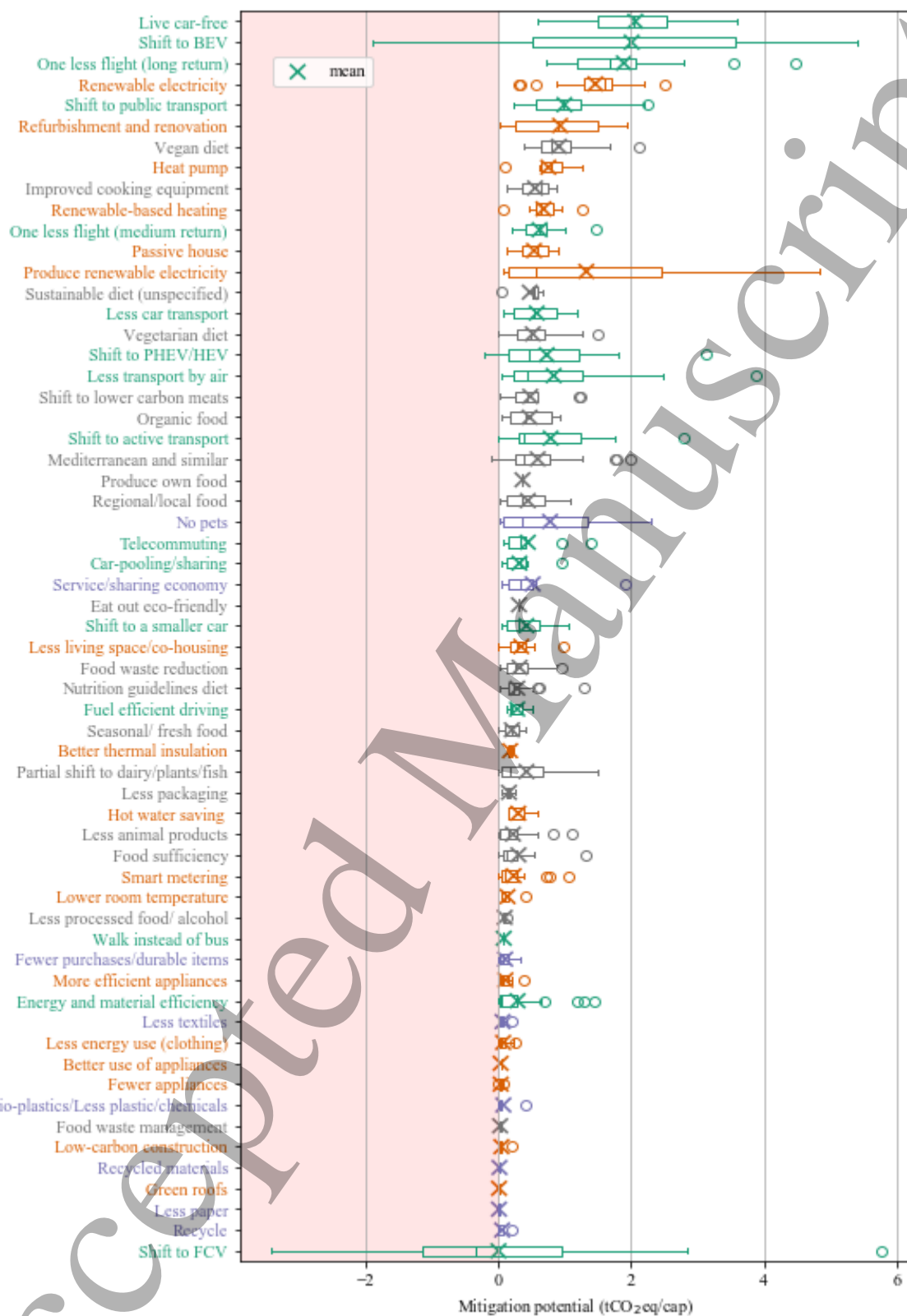
Discussion and conclusions

Mitigation potential of consumption options

One contribution of this study is the systematic provision of mitigation ranges across various consumption domains and the harmonization of results from different methodologies, scopes and assumptions within the same framework (Figure 7). The top consumption options (by medians) include substantial changes in car travel (living car-free, shifting to electric vehicles and public transport), air travel reductions, use of renewable electricity and more sustainable heating (renewable-based heating and heat pump), refurbishment and renovation, a shift to a plant-based diet and improved cooking equipment. The top 10 consumption options together (accounting for the overlap of car travel alternatives) yield an average annual mitigation potential of 9.2 tCO₂eq/cap. While crudely estimated, this indicates a substantial mitigation potential of already available low-carbon consumption options towards achieving the 1.5-2°C target.

Across world regions, the average consumption-based carbon footprints vary between 1.9 and 0.4 tCO₂eq/cap for food, 4.6 and 0.2 tCO₂eq/cap for transport, 3.7 and 0.5 tCO₂eq/cap for housing, and 3.16 and 0.4 tCO₂eq/cap for other consumption^{2,3} (see SM figure 1). United States and Australia stand out with the highest average per capita carbon footprints in our model: with 2.2 and 2.5 tCO₂eq/cap for food, 4.7 and 5.5 tCO₂eq/cap for transport, 5.8 and 4.3 tCO₂eq/cap for housing, and 4.0 and 3.9 tCO₂eq/cap for other consumption, respectively. Yet, the carbon allowances according to the climate targets by 2050

1 are substantially lower: 0.4 tCO₂eq/cap to food, 0.2 to shelter, 0.7 to travel, 0.4 to goods and 0.4 to
 2 services, amounting to a total of 2.1 tCO₂eq/cap¹¹.



3
 4 Figure 7: A summary of all reviewed consumption options, excluding inner values. Negative values (in the red area) represent
 5 the potential for backfire. The x-s represent the average mitigation potential within the same consumption option (options
 6 ordered by medians). SI Data extraction sheet contains an overview of all options.

1
2
3 1 The interconnected nature of these strategies need to be recognized in order to adequately respond in
4 2 mitigating climate change. For example, studies warn about the potential increase in LUC-emissions
5 3 with the shift to organic; yet, if this shift occurs in parallel to shifts in diets and better food waste
6 4 management, the conversion of natural or semi-natural vegetation to cropland may be reduced
7 5 substantially (Figure 4). Furthermore, co-benefits associated with upscaling these mitigation options
8 6 have also been widely discussed^{64,67,116}.

7 Critical appraisal and limitations

8 This review is limited to the English language literature published since 2011. More relevant evidence
9 could be captured if the scope is extended to other languages, e.g. capturing more evidence from non-
10 OECD countries. Moreover, although we used a very comprehensive set of search terms, there is a risk
11 that we missed literature that did not list them in their title, abstract or key words. Furthermore, as we
12 did not perform an extensive search for the other consumption domain, we may have omitted key options
13 and potentials. We may have also missed relevant research through the adoption of machine learning
14 and the focus on peer-reviewed literature. Including grey literature (such as theses and governmental
15 reports) would decrease susceptibility to publication bias and resulting inclination of peer-reviews
16 literature towards more ‘positive’ results’.

17 The included studies often do not report sufficient methodological details in order to judge rigor of the
18 primary data included. The studies differ largely in assessment method and methodological choices,
19 system boundary, and modelling assumptions. For example, most food-related LCAs adopt a system
20 boundary at the farm gate or retail gate¹⁰¹ (thus, suffering from truncation errors), and exclude consumer
21 losses, impacts associated with the consumption and end-of-life stages, and LUC. LCA reviews
22 generally do not publish an a-priori protocol, conduct a comprehensive and transparent search for studies
23 or discuss an explicit set of inclusion/exclusion criteria. Studies lack transparency with regards to critical
24 appraisal and data extraction, and rarely evaluate the heterogeneity statistically (see the CEESAT
25 tool¹¹⁷). IO studies generally disregard end-of-life stages, LUC emissions and the effects on natural
26 carbon stocks.

27 Most studies do not consider feedback effects in the global supply chains (e.g. the wider adoption of
28 vegetarian diets is expected to influence the supply chains of hotels, restaurants, supermarkets).
29 Furthermore, the reviewed studies generally disregard embodied emissions in the new infrastructure
30 needed for the upscale of low-carbon practices, e.g. the infrastructure of renewables, and the associated
31 costs. Large-scale investments in energy-intensive industries and infrastructure have been shown to
32 counter-balance and even outweigh the sectoral carbon efficiency gains, especially in fast-developing
33 countries^{118,119}. Prior analysis of GHG emissions from existing and proposed infrastructure suggests that
34 a cost-effective strategy to reduce committed emissions is to target the early retirement of electricity and
35 industry infrastructure in the presence of affordable low-carbon alternatives¹²⁰. Finally, other
36 environmental indicators such as resource use and scarcity may differ substantially in their implications
37 and prioritization of consumption options^{54,98}.

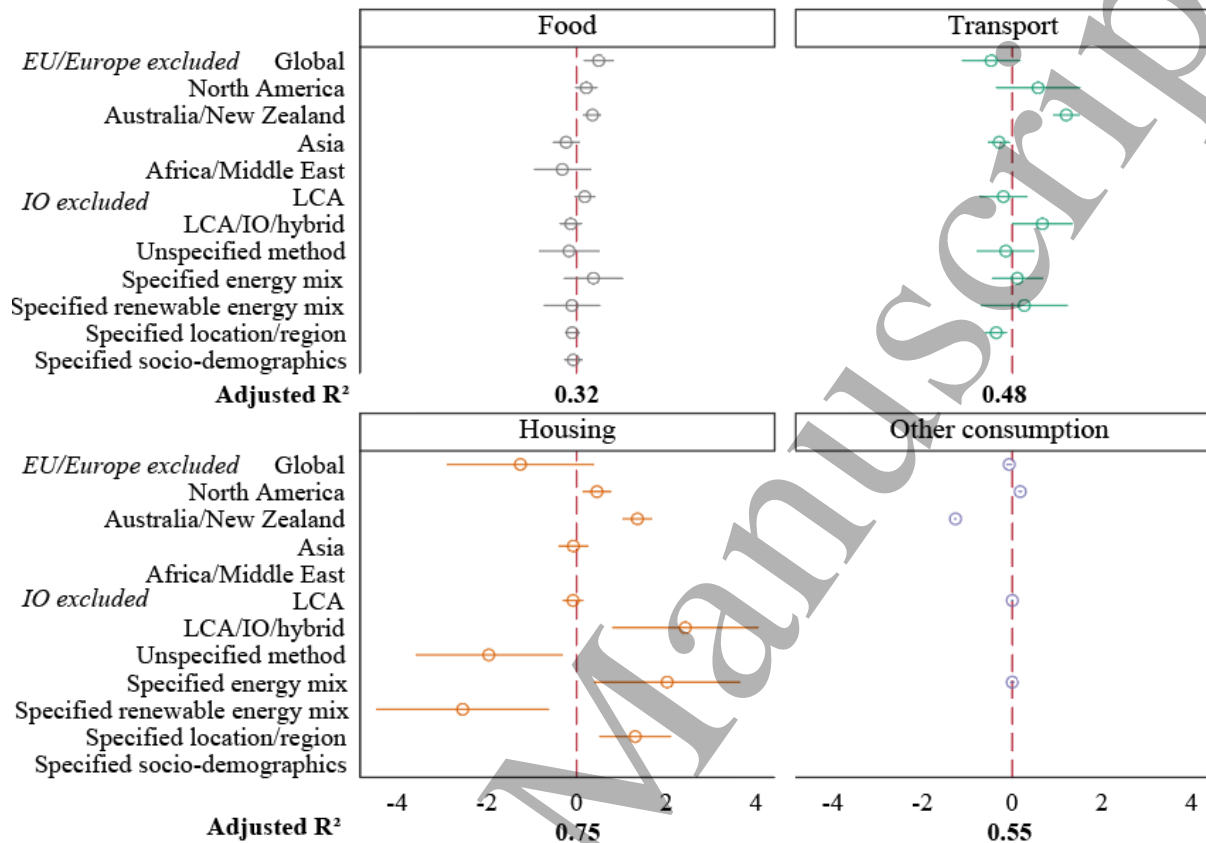
38 A major obstacle with regards to external validity (applicability to our research question) is that LCA
39 reviews, in particular, communicate mitigation potential by various functional units¹⁰² without providing
40 the context of scale. We particularly excluded a number of housing-related LCA reviews as mitigation
41 potential is solely communicated in terms of functional units. This makes the comparison with other
42 environmental assessments (using different methodologies) and carbon targets/budgets very difficult.

43 Modifier effects

44 Considerations about default-option are critical for the assessment of mitigation potential. While some
45 studies present mitigation potential compared to averages, others compare to “high carbon” consumption
46 patterns¹²¹. Furthermore, there is a large uncertainty associated with basic assumptions about human
47 behavior and public acceptability of demand-side mitigation options⁸¹. While we depict absolute
48 reduction potential of various mitigation options – e.g. shift all car travel to public transport – partial

1 adoptions may also be adopted, with relative reduction potential easily calculated as a proportion of the
2 ranges discussed in this paper.

3 Geographical context and other location, impact assessment method, energy mix and carbon intensity
4 and socio-demographics specifications were evaluated in the fixed-effects model as potential factors
5 that influence the mitigation potential ranges within consumption options (Figure 8).



6
7 *Figure 8: Factors contributing to differences in mitigation potential within consumption options. The coefficients are based on*
8 *fixed-effects linear model using clustered standard errors by mitigation options. The dependent variable is the annual carbon*
9 *mitigation potential in tCO₂eq per capita.*

10 For food, mitigation potential estimates from North America, Australia and New Zealand of dietary
11 changes are higher compared to EU estimates, while estimates from Asia are lower. In the context of
12 food, LCA-based results were slightly higher compared to IO-based results. Methodological, geographic
13 and socio-demographic factors explain 32% of the differences in mitigation potential within food-related
14 options. Other potential modifier effects include the accounting of food and cooking losses¹²² and
15 LUC¹⁰¹; the magnitude of change/reduction of calories⁸⁹ and the share imported by air¹¹; nutritional
16 guidelines¹²³; the consideration of rebound effects and knock-on savings from food waste reduction or
17 dietary change including avoided shopping and storage¹⁰⁰; and other social and behavioral
18 characteristics^{102–104}.

19 For transport, mitigation potential estimates from Australia and New Zealand are significantly higher
20 than the European ones, while those from Asia are lower. IO-based estimates are substantially lower
21 than the hybrid estimates in reviewed studies. Geographic and methodological factors attribute to 48%
22 of the differences in mitigation potential within transport-related options. Additional modifiers include
23 fuel and vehicle characteristics^{57,73–75}, travel distance and occupancy rate^{57,61}, energy chain and
24 infrastructure¹²⁴, driving¹²⁴, income group⁶¹ as well as additional technical and behavioral factors¹²⁴.

25 The geographic location, methodology and energy mix are significant for the mitigation potential ranges
26 within housing options, attributing to 75% of the within options variance (Figure 8). The location factor

1 includes contextual factors influencing the supply of energy, e.g. the location of solar panels during
 2 use¹⁰⁹ and geographical differences in energy and heating requirements⁵⁷. Additional modifier effects
 3 include the backup electricity mix, dwelling size, type and lifetime assumption, and additional social
 4 and infrastructural influences.

5 Policy recommendations

6 Finally, we selected the top ranking consumption options and synthesized respective policy
 7 recommendations from the literature. Table 3 communicates a list with the options with the highest
 8 mitigation potential and potential actions towards overcoming the main infrastructural, institutional and
 9 behavioral carbon lock-ins¹²⁵. While the table is informed by the reviewed literature, it should be noted
 10 that we did not conduct a systematic search specifically on targeting actions towards overcoming carbon
 11 lock-ins.

Consumption options with high mitigation potentials	Overcoming infrastructural lock-in	Overcoming institutional lock-in	Overcoming behavioral lock-in
Dietary shift (e.g. vegan, vegetarian)	Change land use practices; Remove investment infrastructure supporting unsustainable and extractive industries	Remove unsustainable subsidies in agriculture, e.g. for meat and dairy; Offer support for alternatives.; Encourage just transition for animal farmers; Better availability of low-carbon options in supermarkets, restaurants, schools, etc; Coordinated efforts of health organizations and government ⁸⁸ ; Ban advertising of high-carbon meats and other high-carbon items.	Encourage low-carbon shared meals ¹²⁶ and diets; Feedbacks for change in social norms and traditions around food consumption ¹²⁶ , e.g. vegan food as default; Decouple veganism/vegetarianism from a particular social identity
Transport mode shift (e.g. active, public transport), car-free	More public transport infrastructure developments for urban and long-distance travel, e.g. cycling lanes, buses, trains; More bike spaces on public transport	Parking and zoning restrictions, e.g. car-free zones and days; Vehicle and fuel tax increases and toll charges; Make driving less convenient in urban areas; Enforce stricter air pollution standards; Ban car advertising	Raising awareness about co-benefits associated with active travel ¹²⁷ ; Social feedback with the visibility of cycling ¹²⁶ ; Decouple car travel from a particular social identity; Improve drivers awareness of cyclers and safety
Reduction in overall travel demand	More compact urban spaces and diverse land use ¹⁶	Allow for flexible working schemes and telecommuting; Halt air travel expansion; Ban flight advertising	Carpooling and carsharing; Encourage telecommuting, moving into denser settlements
Upscaling of electric vehicles	Decarbonize the grid and meet potential additional capacity through renewables; Provision of charging infrastructure	Sustained policy support, e.g. free public charging, tax and fee deductions, subsidies for low-income buyers; Enforce stricter air pollution standards	Tackle charging time acceptance, range anxiety ^{63,70,74}
Renewable-based heating and electricity	Infrastructure investment in renewables	Halt fossil fuel expansion/use and support upscaling of renewables; Incentivize decentralized electricity generation, particularly for low-income households; Enforce stricter air pollution standards; Encourage just transitions for fossil fuel workers; Fossil fuel divestment	Raise public awareness and target NIMBY concerns
Refurbishment and renovation	Energy efficient construction and equipment	Enforce building standards; Encourage investment by dwelling owners and landlords in the fabric of the building and energy efficiency as well as broader home improvements ¹¹⁴ ; Encourage just transitions, e.g. consideration of fuel poverty; Remove inefficiency of listed building	Public awareness around economic and environmental benefits; Reconcile investment incentives with householders' images of home comfort ¹¹⁴

12 *Table 3: A summary of the consumption options with the highest mitigation potential and ways to influence the*
 13 *infrastructural, institutional and behavioral carbon lock-ins associated with them.*

14 Concluding remarks

15 In times of a climate emergency, research and policy urgently needs to move beyond focusing on the
 16 efficiency of production and use of goods and services. The explicit consideration of the absolute scale

1 of consumption and its implications for climate change and well-being is ever more relevant. There is a
 2 need for an open discussion about the overall scale of resource use and emissions and sustainable
 3 consumption corridors¹²⁷ towards remaining within planetary boundaries and satisfying human needs³³.

4 We conducted a comprehensive literature review to summarize and compare the reported GHG ranges
 5 of various consumption options, critically appraise results and uncertainties, clarify the methodological
 6 issues and modifier effects, and identify knowledge gaps to inform future research and policy. The
 7 priorities in terms of consumption options may differ substantially depending on income, geographic
 8 location, energy context, other factors and carbon lock-ins. Still, consumption is intimately connected
 9 to issues of climate change, well-being and sustainability, and thus needs critical attention.

10 We find that the large majority of the household carbon footprints can be mitigation with already
 11 available low-carbon consumption options. Challenging current patterns of consumption and the societal
 12 dynamics through a critical assessment of infrastructural, institutional and behavioral lock-ins and
 13 potential rebound effects, therefore, needs to become a priority for successful climate change mitigation.

14 Acknowledgements

15 D.I. and J.B. received funding from the UK Research Councils under the Centre for Research on Energy Demand
 16 Solutions. D.W. received funding from the European Research Council (ERC) under the European Union's
 17 Horizon 2020 research and innovation programme (MAT_STOCKS, grant agreement No 741950).

18 Data availability

19 The data that support the findings of this study are openly available in the supplementary spreadsheet. Please cite
 20 this article and its digital object identifier (DOI) when making use of the data.

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