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Review of reviews

"Focus on demand-side solutions for transitioning to low-carbon societies"

Quantifying the potential for climate change mitigation of consumption options

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Abstract

Background

Around two-thirds of global GHG emissions are directly and indirectly linked to household consumption, with a global average of about 6 tCO_2eq/cap. The average per capita carbon footprint of North America and Europe amount to 13.4 and 7.5 tCO_2eq/cap, respectively, while that of Africa and the Middle East - to 1.7 tCO_2eq/cap on average. Changes in consumption patterns to low-carbon alternatives therefore present a great and urgently required potential for emission reductions. In this paper, we synthesize emission mitigation potentials across the consumption domains of food, housing, transport and other consumption.

Methods

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

Results and discussion

We establish consumption options with a high mitigation potential measured in tons of CO_2eq/capita/yr. For transport, the options with the highest mitigation potential include living car-free, shifting to a battery electric vehicle, and reducing flying by a long return flight with a median reduction potential of more than 1.7 tCO_2eq/cap. In the context of food, the highest carbon savings come from dietary changes, particularly an adoption of vegan diet with an average and median mitigation potential of 0.9 and 0.8 tCO_2eq/cap, respectively. Shifting to renewable electricity and refurbishment and renovation are the options with the highest mitigation potential in the housing domain, with medians at 1.6 and 0.9 tCO_2eq/cap, respectively. We find that the top 10 consumption options together yield an average mitigation potential of 9.2 tCO_2eq/cap, indicating substantial contributions towards achieving the 1.5-2°C target, particularly in high-income context.

Background

The need for demand reductions

Global greenhouse gas (GHG) emissions (carbon footprints) have been steadily rising, with faster, sizable and immediate CO_2 emissions declines needed to limit cumulative emissions and reach net zero emissions in 2050[1]. Annual GHG emissions must decrease by 45% percent of their 2010-levels by 2030, and reach net-zero by 2050 to limit temperature changes to 1.5°C above preindustrial levels. The potential impacts and risks are substantially lower for a 1.5°C global warming compared with a 2°C, including climate-related risks and threats regarding various ecosystems and human welfare[1]. Global GHG emissions amounted to 6.3 tCO_2eq/cap in 2011[2]; however, these are highly unequally distributed across income groups and countries[3–8]. For example, the average per capita carbon footprint of North America and Europe amount to 13.4 and 7.5 tCO_2eq/cap, respectively, while that of Africa and the Middle East - to 1.7 tCO_2eq/cap on average (SM figure 1). For a population of 8.5 billion by 2030[9], emissions need to decrease to an average of ~2.8 tCO_2eq/cap by 2030, to comply with a pathway of limiting climate change to 1.5°C of global warming. This is broadly in line with other estimates of per capita carbon budgets[10–12].

The exact carbon budget for limiting global warming to 1.5°C is influenced by uncertainty about earth system dynamics, as well as the scale and speed of adoption of negative emission technologies. Almost all of the IPCC scenarios currently assume large-scale adoption of negative emission technologies at massive scales[13–15], which are potentially associated with strong adverse economic and environmental consequences[16], energy constraints (e.g. expanding carbon)[17] and moral hazards because they tempt policy makers to delay mitigation action now[15].

Energy end-use is the least efficient part of the global energy system with the largest improvement potential, where appropriate scaling down of the global energy demand allows for feasible de-carbonization without betting on controversial negative emission technologies or geoengineering. While technological solutions that decarbonize energy supply or capture carbon have to make a significant mitigation contribution, changing consumption offers more flexibility for reducing carbon intensity in the energy supply sector and limit the related supply-side risks[18]. Mitigation scenarios relying more heavily on reduction in the demand of energy services are clearly associated with the lowest mitigation and adaptation challenges[15,19] and provide a range of co-benefits.

Challenging consumption

Behavior, everyday life and cultural norms around consumption have a crucial influence on energy use and embodied emissions, with a high mitigation potential in various consumption domains[18,20,21]. 65% of global GHG emissions, and 50-80% of land, water and material use, can be directly and indirectly linked to household consumption[3]. Income is a major driver of household carbon footprints[5,7,8,22,23], directly affecting purchasing power of households. Changes in household consumption patterns to low-carbon alternatives, such as transport model shifts, home energy reduction and dietary shifts, thus present a great mitigation potential.

Importantly, in the last decade, so-called multiregional input-output models (MRIO) have enabled the systematic analysis of global production and consumption using consistent accounts of global GHG emissions, and taking into account the scale and complexity of international trade and supply chains[24–26]. Consumption estimates derived through MRIOs were the first to fully allocate global emissions to national household consumption (as well as government activities and investments) without double-counting or omitting emissions, thus overcoming a long-standing limitation of single-regional input-output approaches and lifecycle assessment (LCA) studies[27,28]. However, understanding options for change also requires bottom-up detailed information and insights going down to the product-level – which is a challenge for MRIOs as they offer a quite limited product detail. In this context, LCAs are relevant due to their process-specific and highly detailed nature. Here we argue that a combination of bottom-up and top-down approaches provides a robust base for the review of the mitigation potentials of consumption options.

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

For the purpose of this paper, we do not capture mitigation potential associated with other avenues towards social change[21], such as community action and engagement[32,33], policies and incentives, political engagement and non-violent civil disobedience[34] or reductions in overall working time and re-definitions of paid labour[23], which all are highly relevant for challenging societal norms around consumption and tackling climate change. Supply chain actors play a key role for climate change mitigation, having direct agency over the majority of energy and emissions along supply chains[35,36]. Similarly, structural change by governments, ending fossil-fuel support, and providing low-carbon infrastructures, is crucial to enable climate change mitigation[37–39]. We also do not review system-wide effects and potential for income rebound effects[40–42]. Our focus on consumption options should not be interpreted as passing the mitigation responsibility to consumers[43]. Still, a change in consumption practices is needed for reaching net-zero carbon emissions[1,44].

Research questions

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

The primary question consists of the following question components:

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

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

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

Outcome (O): Annual carbon savings measured in per capita CO_2-equivalent reductions

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

We focus on household consumption associated with the three end-use sectors of food, transport and housing as they are highly relevant in terms of consumption-based GHG emissions[3,45], energy[46] and other resource use[3] with some of the highest potential for consumption intervention[29,47].

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

We aim to capture sources of heterogeneity across studies, including system boundary[48], methodological specificities, socio-economic, urban-rural and geographical context among others.

Methods and search results

The review followed the Collaboration for Environmental Evidence Guidelines[49] and it conformed to ROSES reporting standards[50]. It was conducted according to peer-reviewed protocol[51] that was submitted to Environmental Research Letters in March 2019 and approved in April 2019. The approved protocol is openly available online[51].

Deviations from the protocol (outline)

The following changes were made from the final published protocol[51]: 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		**(1) General**	**(2) Transport**	**(3) Food**	**(4) Housing**
	Consumption domains	(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	*(decreas* OR durab* OR eco* OR efficien* OR green* OR longetivity OR natural OR maintain* OR recycl* OR reduc* OR renewabl* OR repair* OR reus* OR “second hand” OR second-hand OR shar* OR sufficien*)*	*(“light weight” OR electric* OR hybrid* OR telecommut* OR telework* OR walk*)*	*(“eat less” OR compost* OR flexitarian OR local OR organic OR season* OR vegan OR vegetarian)*	*(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)))*

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.. See the supplementary material for Scopus formatting.

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

Article screening and eligibility criteria

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

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

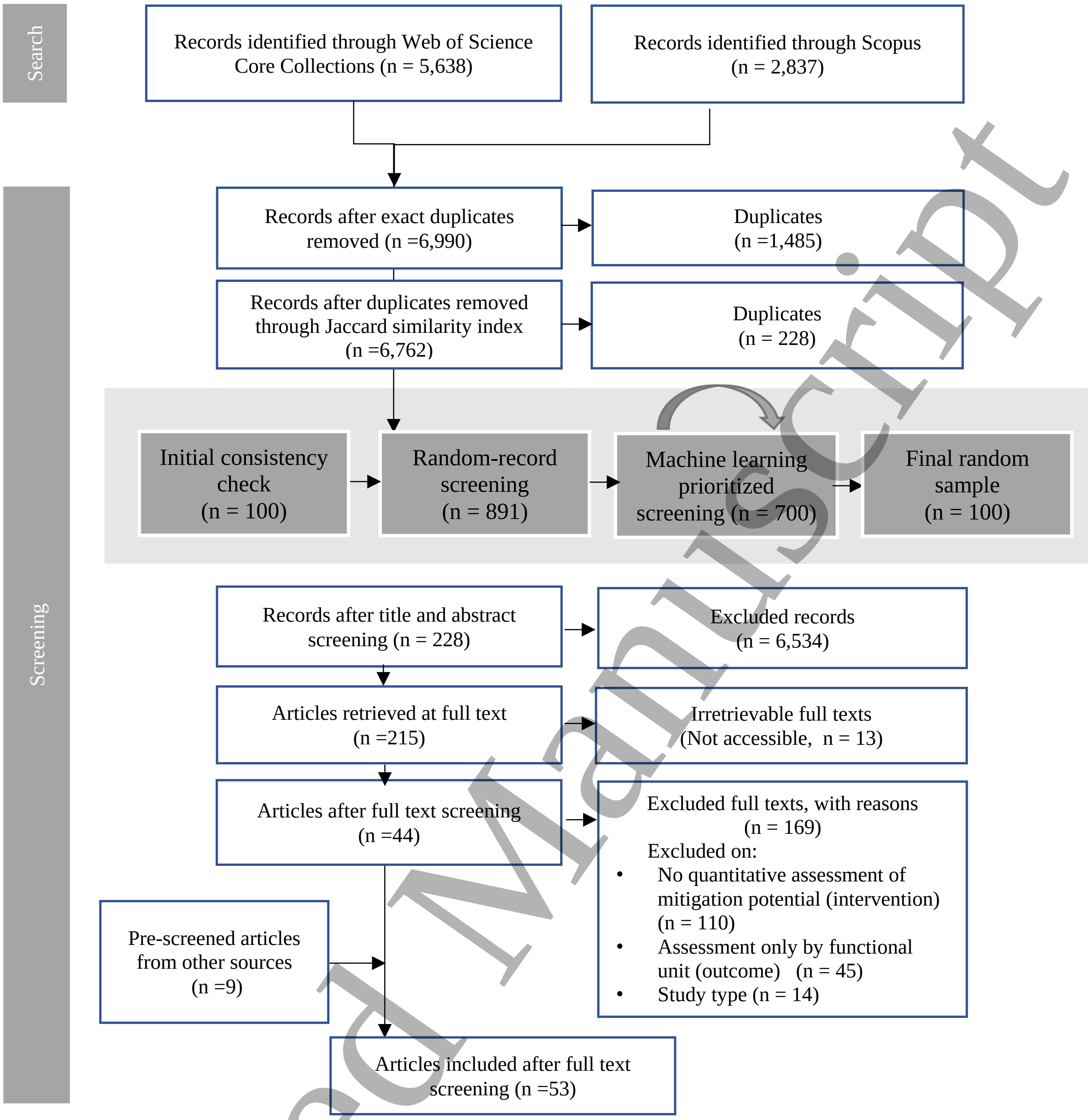

Figure 1: Flow diagram – adapted from the ROSES flow diagram for systematic reviews[128]. See the supplementary data extraction for more detail about excluded articles and the supplemenary materials for details on the methods.

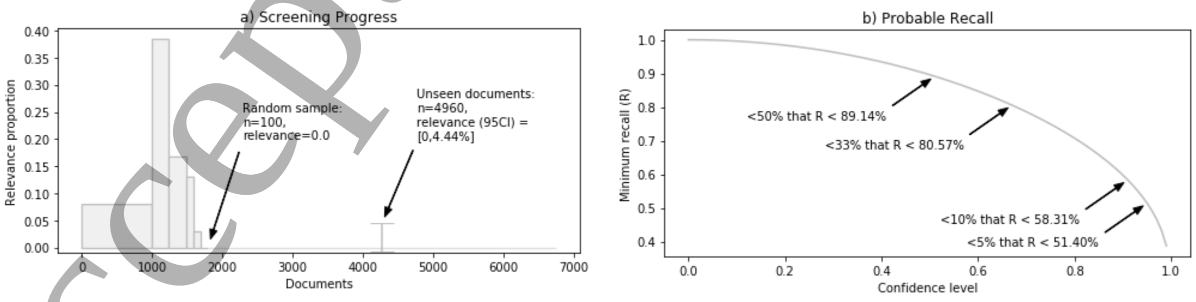

Figure 2: Screening progress (a) and probable recall (b). In a), each bar represents a set of screening decisions, with the width showing the number of documents and the height showing the percentage of them that was relevant. The first bar represents the 991 documents screened at random. The subsequent 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**
Eligible population/ setting	No geographical restriction and focus on household consumption	Mitigation potential not directly linked to households (e.g. government spending)
Eligible intervention: Consumption options by consumption domain	• 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
Outcome: Mitigation potential and lifecycle emissions	Mitigation potential assessed through annual carbon savings in kilograms/tons CO_2-equivalents per capita, converting GHGs (e.g. CO_2, CH_4, N_2O, 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.
Study types	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.

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

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

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

Data extraction and synthesis

We extracted meta-data from each reviewed study, including title, author team, year of publication and data collection, consumption option and domain, geographical context, method, system boundary, carbon metric and GHGs included from the eligible studies. We further extracted the study quantitative findings, e.g. average, standard deviation, number of studies reviewed, min-max range, absolute and relative carbon savings, contextual carbon footprint calculations. Missing or unclear information was requested directly from authors. We recalculated the mitigation potential of consumption options in tons CO_2 equivalents per capita where needed in order to improve comparability across studies.

The baselines considered in the reviewed studies are associated with large uncertainties and different assumptions (e.g. average baseline vs high-carbon baseline). At the same time, the baselines are key for the calculation of mitigation potentials and may largely affect the order of consumption options on the graph. In such cases results should be interpreted with caution.

Data synthesis and potential effect modifiers/reasons for heterogeneity

Included literature is characterized by a large variation in methods, internal validity of studies, coverage of different GHGs, location and timeframe, system boundary, assumptions about uptake rate[56] and other potential sources of heterogeneity. We discussed heterogeneity along with the narrative synthesis of study findings. Where data allowed, we considered the effect modifiers in quantitative synthesis. We used a fixed-effects model to explore the relationship between predictors (various geographical, technical and socio-demographic factors) and outcome variables (mitigation potential per capita) across consumption options as a way to explain the variation in mitigation potential. Using the fixed-effect approach, we control for factors invariant across mitigation options, which we could not include directly in our model.

Review Results

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

Transport

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

There is substantial mitigation potential in reducing air travel for those who fly. *One less flight (long return)* may reduce between 4.5 and 0.7 (mean of 1.9) tCO_2eq/cap, while taking *One less flight (medium return)* – between 1.5 and 0.2 (0.6) tCO_2eq/cap. The two options have a median reduction potential of 1.7 and 0.6 tCO_2eq/cap, respectively. Yet, the number of trips per passenger in 2018 amounted to 2.0 in the United States and to 3.6 and 4.8 in wealthy European countries such as Luxembourg and Norway, with the numbers projected to increase rapidly[60]. Other studies exploring partial reductions in air travel (*Less transport by air*) find an average reduction potential of 0.8 tCO_2eq/cap. The overall mitigation potentials strongly depend on income, as high-income households fly much more[4,5,61].

Reducing car travel is associated with substantial mitigation potential. *Living car-free* has the highest median mitigation potential across all of the reviewed options at 2.0 tCO_2eq/cap, with a range between 3.6 and 0.6 tCO_2eq/cap. Assumptions around vehicle and fuel characteristics as well as travel distance are key for the estimated mitigation potential, with the maximum value in our sample being associated with giving up an SUV[29]. Partial car reductions, captured by the options of *Less car transport*, *Shift to active transport* and *Shift to public transport* in our sample, have an average mitigation potential between 0.6 and 1.0 tCO_2eq/cap. These options are generally limited to replacing short and urban car trips with alternative transportation modes or reducing leisure trips[42,62–64], which constitute a relatively small portion of all travel and its embodied emissions[57,65,66]. Yet, active and public transport alternatives have much lower carbon intensities per travel km[57,67,68]. Active and public transport are characterized by average carbon intensities at 0.00 and 0.09 $kgCO_2eq$/km, while individualized motorized transport at 0.23 $kgCO_2eq$/km[57]. *Telecommuting* practices reduce commute emissions between 1.4 and 0.1 (mean of 0.4) tCO_2eq/cap, while *Car-pooling and car-sharing* and *Fuel efficient driving* have an average carbon savings of 0.3 tCO_2eq/cap. The practice of ride-hailing, or receiving transportation from an unlicensed taxi service, may result in an increase in emissions as a result of "deadheading", the travelled miles without a passenger between hired rides[69]. For example, a non-pooled ride-hailing trip generates 47% greater emissions per mile compared to a private car trip of an average fuel efficiency[69]. The number of passenger sharing the trip makes a substantial difference in terms of mitigation potential, as well as the type of trip that is displaced (e.g. private driving, public transit, walking). Thus, the shift from public transport to active transport[42] offers only marginal mitigation potential per capita (Figure 3).

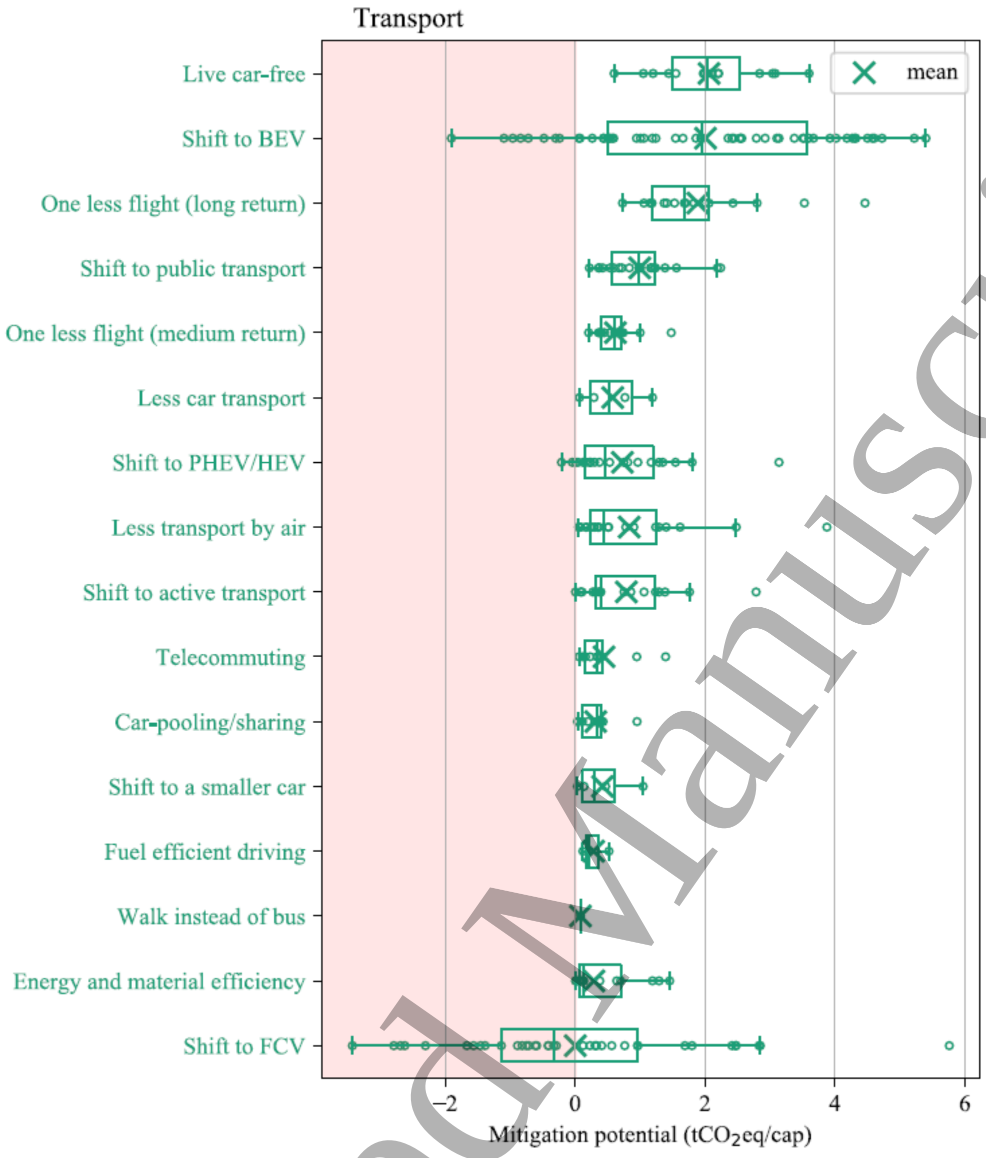

Figure 3: Annual mitigation potential of consumption options for transport measured in tCO_2eq/cap. *The figure is based on a sample of 23 review articles and 16 consumption options. Negative values (in the red area) represent the potential for backfire. The dots represent single reviewed studies and 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 OECD*[70]*, 1000 km in China*[71] *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 tCO_2eq/cap, with an average and median of 2.0 tCO_2eq/cap. Carbon reduction potential varies between 3.1 and -0.2 (mean of 0.7) tCO_2eq/cap for (plug-in) hybrid electric vehicles (PHEV/HEV), and between 5.8 and – 3.4 (mean of 0) tCO_2eq/cap for fuel cell vehicles (FCV). The carbon intensity of the electricity mix (widely varying across countries[70]) 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 results[76]. 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 UK[70]. Fuel consumption is the most influential factor affecting the

GWP of ICEV, HEV and PHEV[74]. PHEV have a similar electricity consumption to that of BEV when driving electric[75]. Strong coal-dependence (when the proportion of coal electricity is 20% or larger)[77] eliminates any potential GHG savings with the shift to FCV. The main advantage of a FCV compared to a BEV is the higher range and quick refilling of the tank[75,77]; yet, the necessary H_2 filling station infrastructure is currently lacking[75]. We noted substantial differences in the system boundary and modelling approaches, which may also influence the mitigation ranges.

Energy and material efficiency (e.g. more efficient combustion engine, lightweight materials, improved fuel economy, cleaner fuels)[73,78–81] brings a reduction between 1.46 and 0.01 (mean of 0.3) tCO_2eq/cap. Yet, there has been a clear trend of increased number of vehicles[64], travelled distance per person[70] and increased mass of light-duty vehicles[80], which offset efficiency improvements with transport emissions still on the rise[64]. Differences in ranges may be explained by assumptions about recycling rates and material substitution factors, vehicle lifetime, class and drive cycle and other factors[78,80].

We could not evaluate annual mitigation potential from biofuels, as most studies communicate mitigation potential in terms of functional unit (e.g. per MJ of fuel), without further discussions of travelled distance and vehicle efficiency. There are large uncertainties around the mitigation potentials of biofuels due to inconsistencies in scope definition (e.g. system boundary and functional unit), assumptions (e.g. impacts of infrastructure and coproduction), technological choices, and data sources[82]. If system boundaries are expanded to include indirect LUC, physical land constraints from food and feed, and biodiversity conservation as well as the temporal effects on natural carbon stocks, biofuels are revealed as less attractive if not detrimental option for climate change mitigation[83,84].

Food

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

The mitigation potential associated with a diet change involving a reduction in the amount of animal products consumed varies between 2.1 and 0.4 tCO_2eq/cap (mean of 0.9 tCO_2eq/cap) for a *Vegan diet*, between 1.5 and 0.01 (0.5) for a *Vegetarian diet*, and between 2.0 and -0.1 (0.6) for *Mediterranean and similar* diet – e.g. Atlantic and New Nordic. The three types of diets have median mitigation potential of 0.9, 0.5 and 0.4 tCO_2eq/cap, respectively. Adopting more *Sustainable diet* or a *Shift to lower carbon meats* is also associated with sizable reductions, with an average annual reduction of 0.5 tCO_2eq/cap. The carbon intensity per calorie/kg of primary product is substantially lower for vegetal foods compared to ruminants, non-ruminants and dairy[11,85–87], with meat producing more emissions per unit of energy due to energy losses at each trophic level[88]. Emissions associated with land use change (LUC) are also most significant for meat-intensive diets[89], due to increases in pasture land and arable land for growing feed. *Nutrition guidelines diets* optimized with regards to health guidelines (generally including a reduction in the red meat intake and increase in plant-based foods) are associated with more moderate potential reductions between 1.3 and 0.01 tCO_2eq/cap (mean of 0.3 tCO_2eq/cap).

Improved cooking equipment is associated with strong mitigation potential amounting to a mean and a median of 0.6 tCO_2eq/cap. Cooking methods, fuels, choice of food and cook-ware, use and management of the cook-ware as well as storage time and space are all relevant factors[90,91].

Other options for carbon footprint reductions in the food domain focus on the production methods, transportation, seasonality and processing of food products. *Organic food* have lower emissions compared to conventionally produced food, with an average annual mitigation potential of 0.5 tCO_2eq/cap and a median of 0.4 tCO_2eq/cap. This mitigation potentials is primarily attributable to the increased soil carbon storage and reductions of fertilizers and other agro-chemicals[92–94]. Yet, increases in GHG emissions from organic food for the same diet are not uncommon[92,93,95], due to lower crop and livestock yields of organic agriculture and the potential increase in production and associated LUC[92]. Opting for *Regional and local food* and *Seasonal and fresh food* involves average reductions of 0.4 and

0.2 tCO_2eq/cap. One of the advantages of producing and consuming food in its natural season is that it does not require high-energy input from artificial heating or lighting[91,96], thus reducing the embodied GHG emissions. Producing and consuming locally may reduce emissions from transportation and abate impact displacement overall[91], provided there are not large increases in energy requirements (e.g. in the case of heated greenhouse production or through the use of fertilizer[97,98]). Regional production requiring the use of heating systems (e.g. fresh vegetables in the beginning of the growing season) may be associated with higher emissions compared to even substantial long-distance transport emissions from production sites without heating[99].

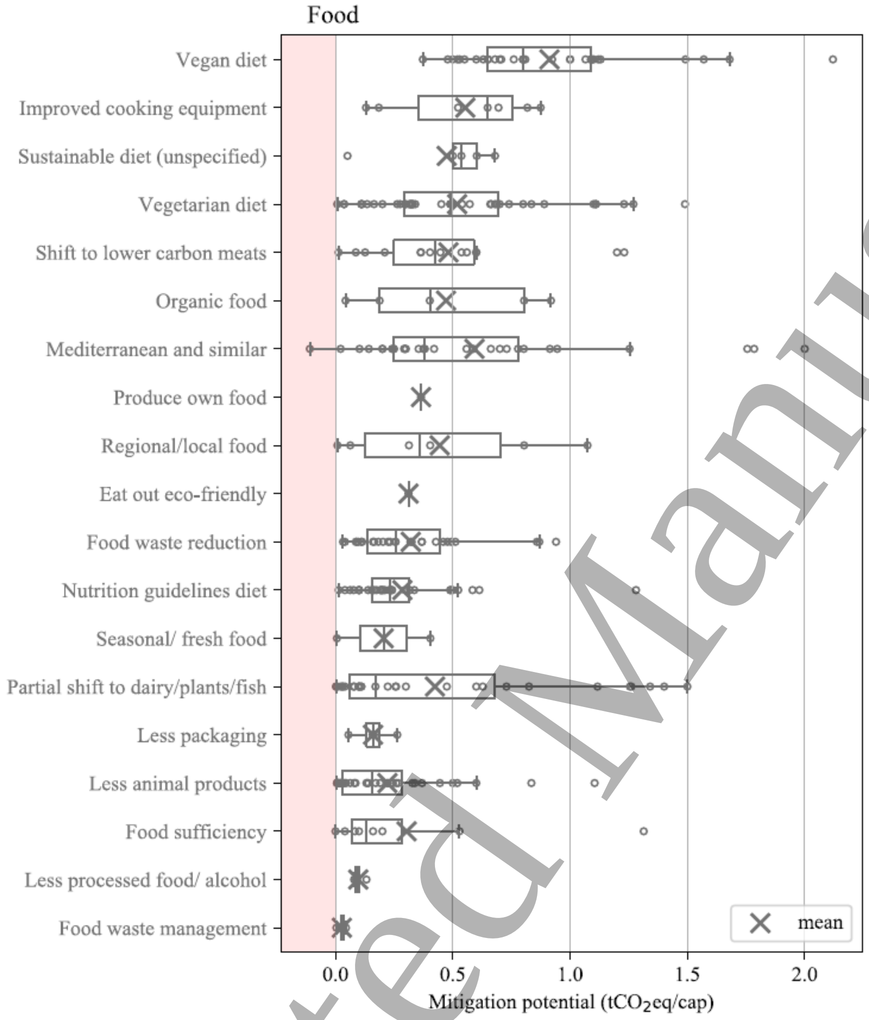

Figure 4: Annual mitigation potential of consumption options for food measured in tCO_2eq/cap. The figure is based on a sample of 32 review articles and 19 consumption options. Negative values (in the red area) represent the potential for backfire. The dots represent single reviewed studies and the x-s – 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.

We also note substantial mitigation potential associated with the reduction in consumed food and waste. *Food sufficiency* – implying a reduction in the overall food intake – and *Food waste reduction* options mitigate an average of 0.3 tCO_2eq/cap and a median of 0.1 tCO_2eq/cap. Food waste studies generally make a distinction between avoidable and potentially avoidable waste, which are said to amount to 80%[100] of all food waste. *Food waste management* of unavoidable food waste is associated with more modest average mitigation potential of 0.03 tCO_2eq/cap.

There are large uncertainties[92,101–104] associated with environmental (e.g. emissions arising from biological processes, LUC and highly integrated production such as beef and dairy), nutritional data (e.g. consumption and waste, weighting factors for gender and age). Impact assessment studies generally do not consider emissions associated with LUC[101], 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 unequal[105]. 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 consumption[105].

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 material[106], embodied and operational energy per m^2 of living space, unit of fuel, thermal insulation per surface unit[107] 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) tCO$_2$eq/cap (Figure 5). The two options have median mitigation potential of 1.6 and 0.6 tCO$_2$eq/cap, respectively. The mitigation potential of adopting renewable technologies is dependent on the energy source[108] and a wide range of contextual factors[109] – 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 maintained[109].

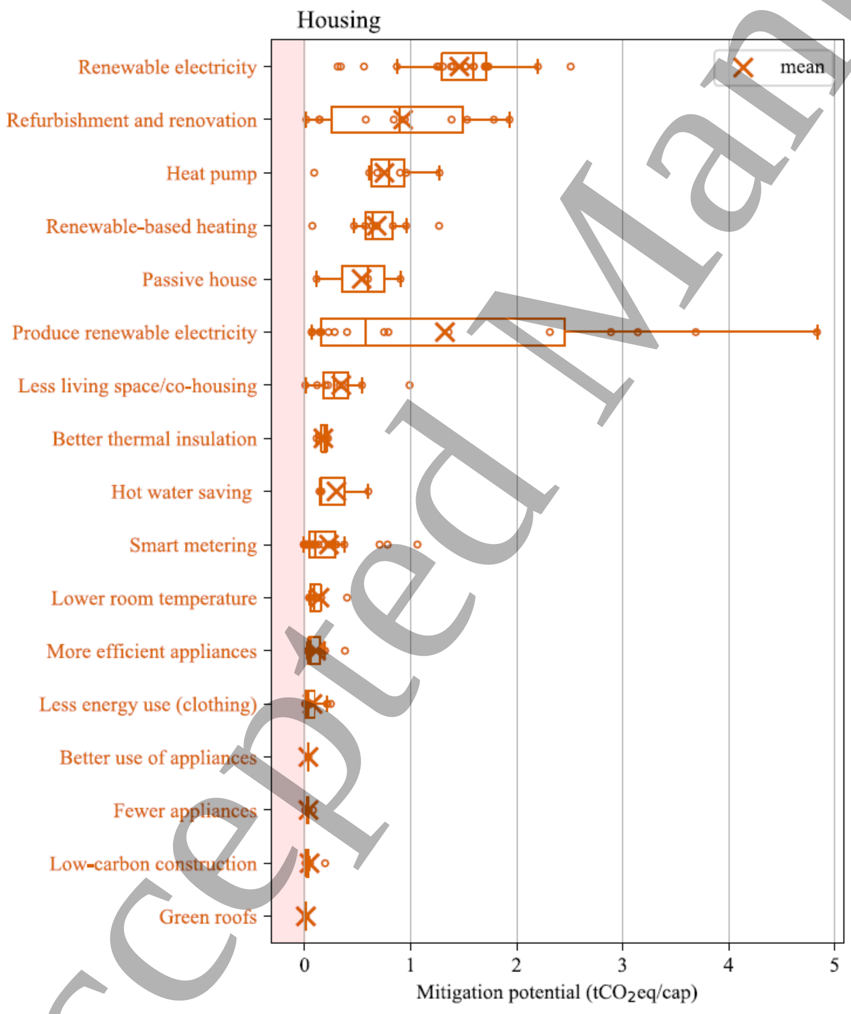

Figure 5: Annual mitigation potential of consumption options for housing measured in tCO$_2$eq/cap. The figure is based on a sample of 13 review articles and 17 consumption options. Negative values (in the red area) represent the potential for backfire. The dots represent single reviewed studies and 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.

Other effective infrastructure-related options associated with space heating include *Refurbishment and renovation*, opting for *Heat pump* and *Renewable-based heating*, which offer an average mitigation potential of 0.9, 0.8 and 0.7 tCO_2eq/cap, respectively. The shift to a *Passive house* is associated with an average reduction potential of 0.5 tCO_2eq/cap (based on estimates by three studies), excluding GHG emissions associated with changes in infrastructure. The carbon intensity of materials and sources[62,108], infrastructure[62] and geographical differences in energy and heating requirements and temperature tolerance[57] are all key factors for the absolute mitigation potential associated with these options. The reviewed mitigation potential of *Smart metering* varies between 1.1 and 0 tCO_2eq/cap, with an average of 0.2 tCO_2eq/cap. *Smart metering* improves household awareness of their energy consumption and support energy reduction activities (e.g. it may encourage retrofitting of houses or change of appliances and equipment)[110]. These indirect effects are generally not captured in pilot studies[110]. Factors such as climate differences, dwelling type and share of renewables in the local grid are of crucial importance for the carbon savings potential[110].

Less living space and co-housing – which includes options such as smaller living space (and hence less heating and construction), collective living with others and renting out guest rooms for other people to live in – offer carbon reductions of up to 1.0 tCO_2eq/cap, and an average of 0.3 tCO_2eq/cap. When people live together, they tend to share space heating, cooling, lighting and the structure of the common living space, appliances, tools and equipment[23,111,112]. While these estimates of household economies of scale from shared living are only limited to the housing domains, sharing within households extends to other types of consumption (e.g. sharing food and cooking together)[112]. Furthermore, the energy use reductions associated with an additional household member tend to be lower for large households compared to small households[112]. As building size is the most important factor for home energy consumption, downsizing may substantially reduce housing-related emissions and energy use[113]. However, there are significant structural (e.g. lack of adequate alternatives), psychological (e.g. attachment) and security barriers (e.g. loss of ownership) related to downsizing[113].Other behavioral interventions such as *Hot water saving* and *Lowering room temperature* by 1-3°C bring about an average saving of 0.3 and 0.1 tCO_2eq/cap, respectively.

Other consumption

Finally, other consumption options with substantial mitigation potential include not having a pet and sharing and consumption of services instead of goods with median mitigation potential around 0.3 tCO_2eq/cap (Figure 6). The service/sharing economy includes options such as opting for local, non-market and community services, share and repair. Strategies encouraging sharing include adequate design and infrastructure for durability, recyclability, reuse and product longevity[81] and incentives for multi-household living[57], grassroots initiatives and downsizing[32,114]. Yet, studies also warn that peer-to-peer strategies do not necessarily translate into carbon footprint reductions due to extra income and induced consumption[115].

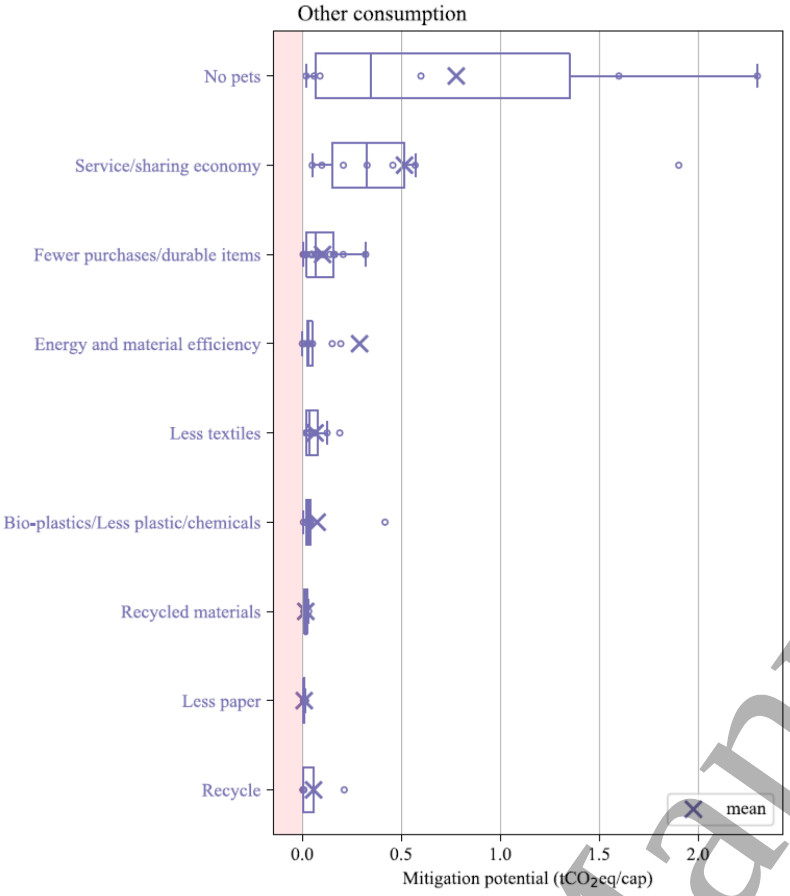

Figure 6: Annual mitigation potential of consumption options for other consumption measured in tCO_2eq/cap. The figure is based on a sample of 10 review articles and 9 consumption options. Negative values (in the red area) represent the potential for backfire. The dots represent single reviewed studies 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 tCO_2eq/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 tCO_2eq/cap for food, 4.6 and 0.2 tCO_2eq/cap for transport, 3.7 and 0.5 tCO_2eq/cap for housing, and 3.16 and 0.4 tCO_2eq/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 tCO_2eq/cap for food, 4.7 and 5.5 tCO_2eq/cap for transport, 5.8 and 4.3 tCO_2eq/cap for housing, and 4.0 and 3.9 tCO_2eq/cap for other consumption, respectively. Yet, the carbon allowances according to the climate targets by 2050 are substantially lower: 0.4 tCO_2eq/cap to food, 0.2 to shelter, 0.7 to travel, 0.4 to goods and 0.4 to services, amounting to a total of 2.1 tCO_2eq/cap[11].

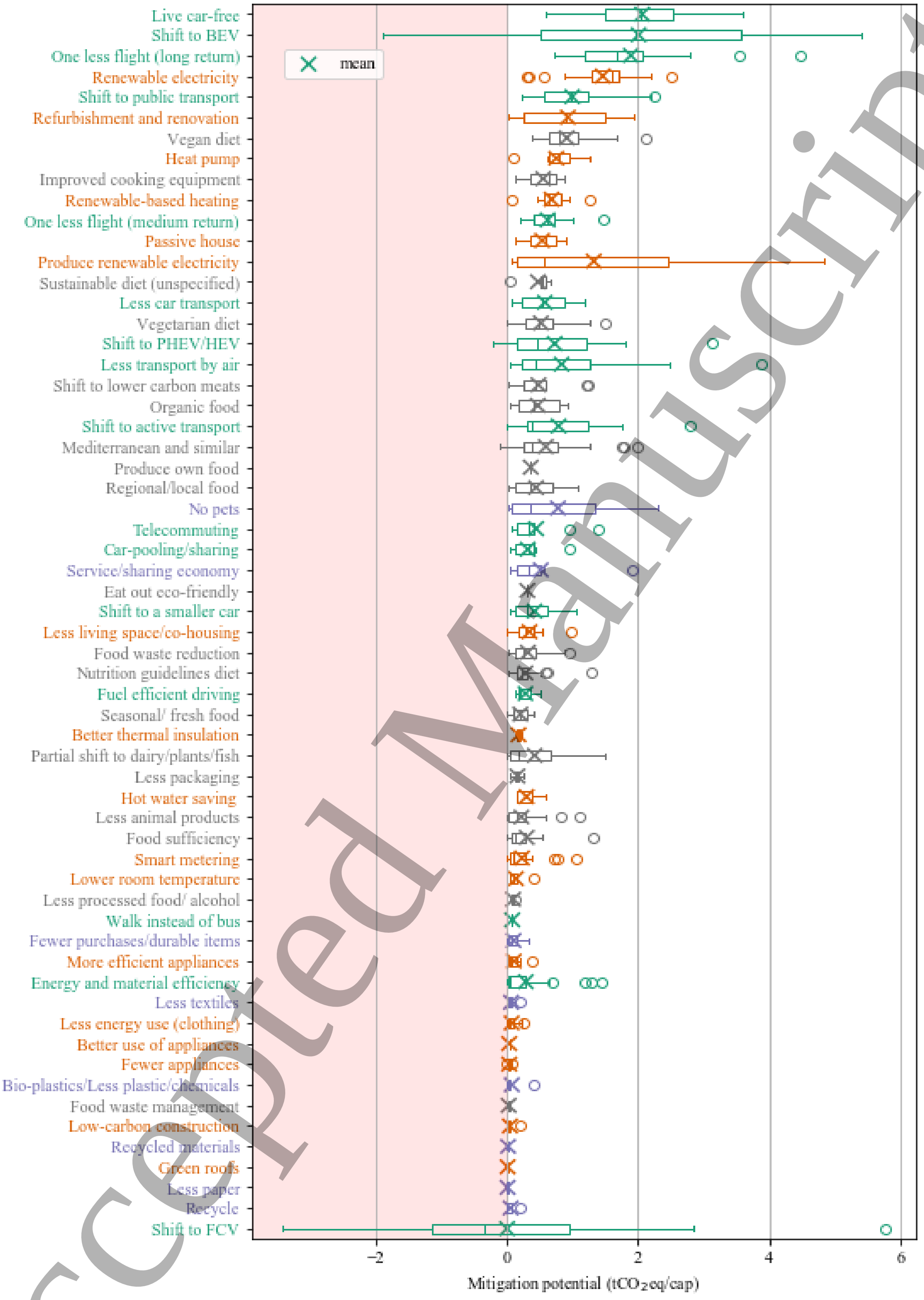

Figure 7: A summary of all reviewed consumption options, excluding inner values. Negative values (in the red area) represent the potential for backfire. The x-s represent the average mitigation potential within the same consumption option (options ordered by medians). SI Data extraction sheet contains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

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

Critical appraisal and limitations

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

The included studies often do not report sufficient methodological details in order to judge rigor of the primary data included. The studies differ largely in assessment method and methodological choices, system boundary, and modelling assumptions. For example, most food-related LCAs adopt a system boundary at the farm gate or retail gate[101] (thus, suffering from truncation errors), and exclude consumer losses, impacts associated with the consumption and end-of-life stages, and LUC. LCA reviews generally do not publish an a-priori protocol, conduct a comprehensive and transparent search for studies or discuss an explicit set of inclusion/exclusion criteria. Studies lack transparency with regards to critical appraisal and data extraction, and rarely evaluate the heterogeneity statistically (see the CEESAT tool[117]). IO studies generally disregard end-of-life stages, LUC emissions and the effects on natural carbon stocks.

Most studies do not consider feedback effects in the global supply chains (e.g. the wider adoption of vegetarian diets is expected to influence the supply chains of hotels, restaurants, supermarkets). Furthermore, the reviewed studies generally disregard embodied emissions in the new infrastructure needed for the upscale of low-carbon practices, e.g. the infrastructure of renewables, and the associated costs. Large-scale investments in energy-intensive industries and infrastructure have been shown to counter-balance and even outweigh the sectoral carbon efficiency gains, especially in fast-developing countries[118,119]. Prior analysis of GHG emissions from existing and proposed infrastructure suggests that a cost-effective strategy to reduce committed emissions is to target the early retirement of electricity and industry infrastructure in the presence of affordable low-carbon alternatives[120]. Finally, other environmental indicators such as resource use and scarcity may differ substantially in their implications and prioritization of consumption options[54,98].

A major obstacle with regards to external validity (applicability to our research question) is that LCA reviews, in particular, communicate mitigation potential by various functional units[102] without providing the context of scale. We particularly excluded a number of housing-related LCA reviews as mitigation potential is solely communicated in terms of functional units. This makes the comparison with other environmental assessments (using different methodologies) and carbon targets/budgets very difficult.

Modifier effects

Considerations about default-option are critical for the assessment of mitigation potential. While some studies present mitigation potential compared to averages, others compare to "high carbon" consumption patterns[121]. Furthermore, there is a large uncertainty associated with basic assumptions about human behavior and public acceptability of demand-side mitigation options[81]. While we depict absolute reduction potential of various mitigation options – e.g. shift all car travel to public transport – partial adoptions may also be adopted, with relative reduction potential easily calculated as a proportion of the ranges discussed in this paper.

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

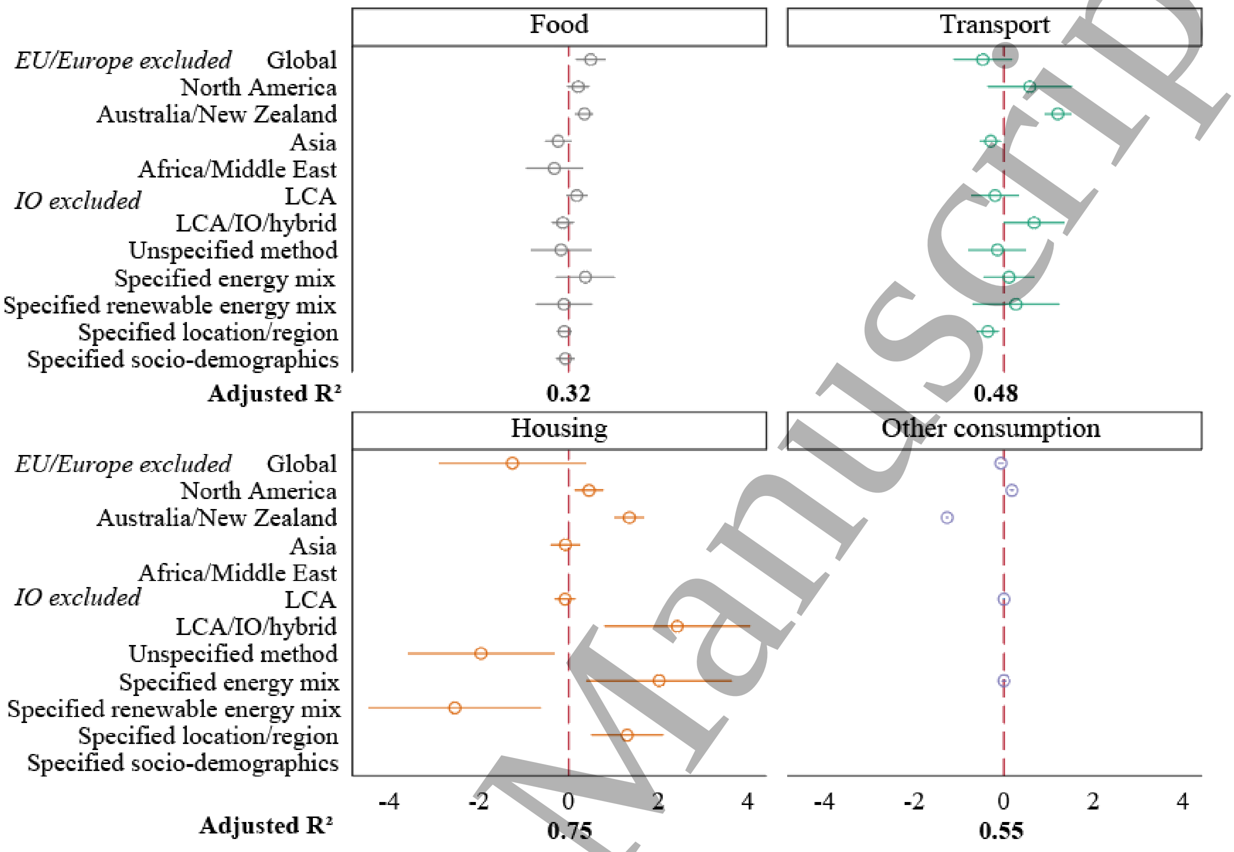

Figure 8: Factors contributing to differences in mitigation potential within consumption options. The coefficients are based on fixed-effects linear model using clustered standard errors by mitigation options. The dependent variable is the annual carbon mitigation potential in tCO₂eq per capita.

For food, mitigation potential estimates from North America, Australia and New Zealand of dietary changes are higher compared to EU estimates, while estimates from Asia are lower. In the context of food, LCA-based results were slightly higher compared to IO-based results. Methodological, geographic and socio-demographic factors explain 32% of the differences in mitigation potential within food-related options. Other potential modifier effects include the accounting of food and cooking losses[122] and LUC[101]; the magnitude of change/reduction of calories[89] and the share imported by air[11]; nutritional guidelines[123]; the consideration of rebound effects and knock-on savings from food waste reduction or dietary change including avoided shopping and storage[100]; and other social and behavioral characteristics[102–104].

For transport, mitigation potential estimates from Australia and New Zealand are significantly higher than the European ones, while those from Asia are lower. IO-based estimates are substantially lower than the hybrid estimates in reviewed studies. Geographic and methodological factors attribute to 48% of the differences in mitigation potential within transport-related options. Additional modifiers include fuel and vehicle characteristics[57,73–75], travel distance and occupancy rate[57,61], energy chain and infrastructure[124], driving[124], income group[61] as well as additional technical and behavioral factors[124].

The geographic location, methodology and energy mix are significant for the mitigation potential ranges within housing options, attributing to 75% of the within options variance (Figure 8). The location factor includes contextual factors influencing the supply of energy, e.g. the location of solar panels during use[109] and geographical differences in energy and heating requirements[57]. Additional modifier effects include the backup electricity mix, dwelling size, type and lifetime assumption, and additional social and infrastructural influences.

Policy recommendations

Finally, we selected the top ranking consumption options and synthesized respective policy recommendations from the literature. Table 3 communicates a list with the options with the highest mitigation potential and potential actions towards overcoming the main infrastructural, institutional and behavioral carbon lock-ins[125]. While the table is informed by the reviewed literature, it should be noted that we did not conduct a systematic search specifically on targeting actions towards overcoming carbon 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[57]; 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]

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

Concluding remarks

In times of a climate emergency, research and policy urgently needs to move beyond focusing on the efficiency of production and use of goods and services. The explicit consideration of the absolute scale of consumption and its implications for climate change and well-being is ever more relevant. There is a need for an open discussion about the overall scale of resource use and emissions and sustainable consumption corridors[127] towards remaining within planetary boundaries and satisfying human needs[33].

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

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

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Data availability

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

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