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ISBN 978-82-326-3266-4 (printed version)
ISBN 978-82-326-3267-1 (electronic version)
ISSN 1503-8181

Doctoral theses at NTNU, 2018:238

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Thesis for the degree of Philosophiae Doctor

Trondheim, August 2018

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Printed by Skipnes Kommunikasjon as

Preface

The thesis is submitted to the Faculty of Engineering Science (IV) at the Norwegian University of Science and Technology (NTNU) in partial fulfilment of the requirements for the degree of Philosophiae Doctor. The work was carried out at the Industrial Ecology Programme (IndEcol) and the Department of Energy and Process Engineering (EPT), under the supervision of Prof. Richard Wood and co-supervision of Prof. Edgar G. Hertwich and Dr. Konstantin Stadler. The thesis was largely funded by the GLAMURS (Green Lifestyles, Alternative Models and Upscaling Regional Sustainability) project financed by the European Union's seventh framework program (contract 613420).

Contents

Abstract

The importance of assessing household environmental impacts for sustainable consumption, and sustainability overall, has been a main motivation for this thesis. There is a need to shift to consumption patterns that exert lower pressure on the environment, while still satisfying human needs. At the same time, mitigation strategies often give little priority to consumption-based environmental impacts and the context in which impacts take place.

It is the aim of this thesis to assess consumption-based impacts from a system perspective, exploring various impacts (carbon, land, materials etc.), levels (from the macro and the country, to the micro and the individual), lifecycle stages, stakeholder groups and consumption activities. The global assessment of household environmental impacts adopts four environmental footprint indicators to quantify and compare total and per capita impacts across 43 countries and 5 rest-of-the-world regions. With their consumption, households contribute to a substantial share of impacts, more than 60% of global GHG emissions and between 50 and 80% of total land, material and water use. The footprints are unevenly distributed with the most impactful consumption being that of the wealthy. Spatial differences of GHG emissions are further explored, based on consumption inventory of 177 regions within the EU. Inter-regional assessments may be useful for the harmonization of national and international climate targets with subnational environmental actions and policies. The analysis highlights the substantial differences in carbon contribution.

Four case study regions in the EU are further explored using a survey on behavioral, attitudinal, contextual, life satisfaction and socio-demographic factors. First, based on observed differences in highly relevant domains of mobility and housing, key elements for reduced emissions are discussed including reduced settlement density, car ownership rates, income and travel distances, as well as changes in dwelling standards and larger household sizes. Second, an assessment of sustainability-focused grassroots initiative members ascertains their reduction in carbon emissions and enhancement in well-being. Particularly, grassroots initiative members have 43% lower carbon footprints for food and 86% for clothing compared to their socio-economic and demographic counterparts from the same regions. Initiative members also show higher life satisfaction compared to the control group, being 11-13% more likely to evaluate their life positively. Finally, increases in income are not associated with increases in total emissions for members, while a strong income-footprint link is confirmed for non-members. Quantifying multi-level, multi-criteria and long-term effects of various mitigation strategies still poses challenges for future research and policy in this area.

Acknowledgements

I would like to acknowledge my supervisors, Richard Wood, Edgar Hertwich and Konstantin Stadler, for their invaluable support and multiple acts of kindness towards me throughout the PhD years. This PhD thesis builds on the solid foundation that you all have provided. Richard, you adopted me and have been watching out for me since. For your gentle and humble presence, genuine nature, open door, and for all creative solutions to keep me employed, I am so grateful. Thank you! Edgar, you trusted in me at a time when I had not yet learned to trust in myself. When I needed it the most. Your serene attitude, empathetic smile and wise advice have been a blessing throughout the years. Konstantin, thank you for your support, friendship and kindness, and of course all of the largely inappropriate jokes that made me laugh so many times!

I would like to acknowledge all my co-authors for their contributions to this thesis. Thank you, Gibran. You are here, and you have been here for it all. For that, for the urban walks, for the questions, for the answers, for the hard learnings, I appreciate you and the time we shared. Thank you, Kjartan, Arnold, Patricia, Carine, Adina, Karen, Irina, Giuseppe, and Ricardo. I truly appreciate learning from you, and all the inspiring discussions, new perspectives, pep talks and good humor that we shared. A special thanks to Helen, my favorite eutrophication guru, and to Angela for helping communicate that what needs to be communicated.

I would like to thank all my colleagues at the Industrial Ecology Programme. I appreciate the time that we shared and the lively discussions, cabin trips, coffee breaks, the cake obsessions. I would also like to acknowledge my colleagues from the GLAMURS consortium. I am so happy to have gotten the chance to meet you, and brainstorm with you for a sustainable future. I would like to thank my family and friends for their love and care through the ups and downs of my years in Trondheim. I have been so blessed to share with you and I love you beyond. Friends, colleagues and teachers, I trust that you all know how appreciated you are, now and always. Благодаря!

Thank you, Loup. Thank you, love.

List of publications

This thesis is based on the four papers listed below as "Primary publications", where Diana Ivanova was a main contributor in during her work as a PhD candidate. In addition, she has contributed as a co-author to several articles and project deliverables, listed below as "Additional publications".

Primary publications

1. Ivanova, D.*; Stadler, K.; Steen-Olsen, K.; Wood, R.; Vita, G.; Tukker, A.; Hertwich, E.G. Environmental impact assessment of household consumption. *Journal of Industrial Ecology* **20,** 526–536 (2016). *Author contribution: data analysis, visualization, and writing of the article.*

2. Ivanova, D.*; Vita, G.; Steen-Olsen, K.; Stadler, K.; Melo, P.C.; Wood, R.; Hertwich, E.G. Mapping the carbon footprint of EU regions. *Environmental Research Letters* **12,** 1–13 (2017). *Author contribution: research co-design, method and tool development, data analysis, visualization, and writing.*

3. Ivanova, D.*; Vita, G.; Wood, R.; Lausselet, C; Dumitru, A.; Krause, K.; Macsinga, I.; Hertwich, E.G. Carbon mitigation in domains of high consumer lock-in. *Global Environmental Change* **52**, 117-130 (2018). *Author contribution: research co-design, method development, data analysis, visualization, and writing.*

4. Vita, G.[1]; Ivanova, D.[1]*; Dumitru, A.; García-Mira, R.; Carrus, G.; Stadler, K.; Krause, K.; Wood, R.; Hertwich, E.G. Members of environmental grassroots initiatives reconcile lower carbon emissions with higher well-being. *In Review in Nature Communications* (2018). [1]Shared first authorship. *Author contribution: research co-design, method development, data analysis, visualization, and writing.*

Additional publications

1. Hamilton, H.A.; Ivanova, D.; Stadler, K.; Merciai, S.; Schmidt, J.; van Zelm, R.; Moran, D.; Wood, R.* Trade and the role of non-food commodities for global eutrophication. *Nature Sustainability* **1**, 314-321 (2018). *Author contribution: data analysis, data interpretation, writing and manuscript editing.*

2. Wood, R.*; Moran, D.; Stadler, K.; Ivanova, D.; Steen-Olsen, K.; Tisserant, A.; Hertwich, E.G. Prioritizing Consumption-Based Carbon Policy Based on the Evaluation of Mitigation Potential Using Input-Output Methods. *J. Ind. Ecol.* **22,** 540–552 (2017). *Author contribution: case study analysis, visualizations, writing and manuscript editing.*

3. Vita, G.*; Lundström, J.R.; Quist, J.; Hertwich, E.G.; Ivanova, D.; Stadler, K.; Wood, R. Alternative consumption scenarios to curb European environmental impact: Connecting local

visions to global consequences. *Prepared for GLAMURS special edition in Ecological Economics.* (2018) *Author contribution: data collection, visualization, and manuscript editing.*

Project deliverables

D3.2: Report on the relationships among psychological, economic and political/policy factors, Section on "Innovative carbon footprinting: arguments for the inclusion of behavioral and lifestyle indicators into footprint calculations", 2015. Ivanova, D.; Vita, G.; *Lead Partner D3.2: Roma Tre University, Italy.*

D5.8: Case Study Report. The region of Donau-Böhmerwald, Austria, 2016. Lauer, P.; Omann, I.; Jungmeier, P.; Krause, K.; Thronicker, I.; Petri, M.; Ivanova, D. *Lead Partner D5.8: Helmholtz Centre for Environmental Research – UFZ, Germany.*

D7.1: Documentation of the environmental sustainability modelling methodology adopted, 2015. Hertwich, E.G.; Ivanova, D. *Lead Partner D7.1: NTNU, Norway.*

D7.2: Environmental footprinting for case studies – tools and documentation, 2016. Vita, G., Ivanova, D.; Stadler, K.; Kammerlander, M.; Alge, S. *Lead Partner D7.2: NTNU, Norway.*

D7.3: Analysis of current impact of lifestyle choices and scenarios for lifestyle choices and green economy developments, 2016. Vita, G.; Ivanova, D. Lundström, J.R.; Tisserant, A.; Stadler, K.; Quist, J.; Smulders, S.; Wood, R. *Lead Partner D7.3: NTNU, Norway.*

Other

Ivanova, D.; Vita, G.; Steen-Olsen, K.; Stadler, K.; Melo, P.C.; Wood, R.; Hertwich, E.G. More stuff = more climate change? *Science Journal for Kids* (2017).

Ivanova, D. Environmental impact assessment of household consumption. *Blog entry for the International Society for Industrial Ecology.* (2017).

1. Introduction

1.1. The sustainability challenge

In our transition to an industrialized society, we have triggered environmental changes at an unprecedented and unsustainable rate to the planet's climate, ecosystems and resource availability moving to what is widely referred to as the Anthropocene[1–4]. These environmental changes have grown with the rapid growth of population, technology and affluence[3,5]. As a result, there has emerged a widening gap between the cultural, social and economic realms, and the biophysical realities of our environment[6].

The goal to achieve sustainability is to meet society's needs without compromising the needs of future generations[7]. Sustainability calls for the integration of human activity into limits imposed by planetary boundaries. Global sustainability challenges are closely interconnected, while they are often studied and managed separately[7]. A reductionist focus on individual components of an integrated global system is prevalent, although it may overlook critical links across system components[7]. Progressing towards global sustainability, thus, requires a systems approach coupling human and natural systems[7].

Scientists have attempted to define and quantify the biophysical pressures and boundaries at the planetary scale. The planetary boundary (PB) framework, for example, explores the "safe operating space" for human development, identifying nine boundaries critical for the stable functioning of the Earth System and a prerequisite for a human society to thrive[8]. It considers the changes that humans cause to Earth's climate, land and freshwater resources, ecosystems and biodiversity, ocean and atmospheric chemistry, and biogeochemical flows[3,8]. Seven of these boundaries have been quantified, of which four are currently transgressed (biosphere integrity, climate change, biogeochemical flows and land-system change) (figure 1)[8,9].

There has also been another advancement towards understanding the link between biophysical processes and human activity – the estimation of environmental footprint indicators for various biophysical resource flows[10]. These indicators present a quantifiable basis for the understanding of the environmental implications of human activity, particularly, resources consumed (such as natural capital) and waste generated[7]. This advancement complements the PB framework (and territorial approaches) with consumption-based accounting (CBA) highlighting the driving forces behind the pressure on ecological assets[11]. CBA assigns responsibility to the final consumer accounting for the embodied impacts in domestic production and international trade[10].

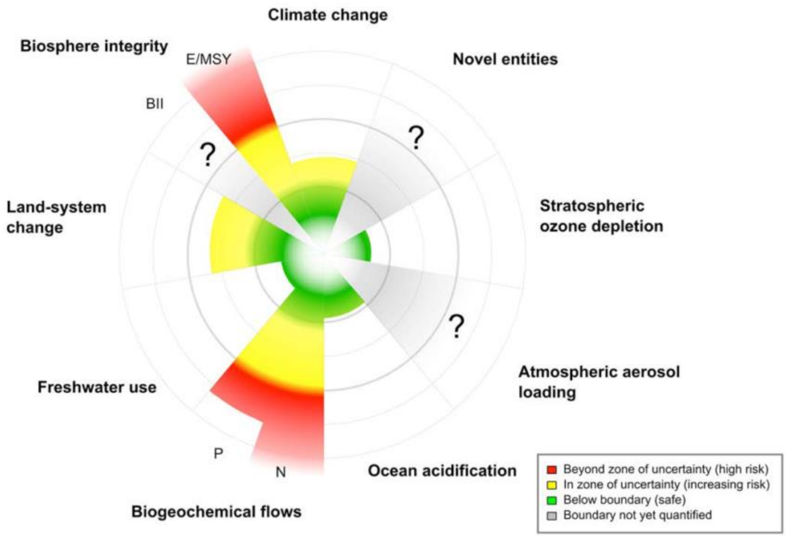

Figure 1: 2015-status of the control variables for seven of the nine planetary boundaries. Source: Steffen et al. (2015)[8]

CBA has been implemented in a "footprint family" approach, where the consideration of multiple impacts enables stakeholders to consider various sustainability limits simultaneously[11]. Each environmental footprint indicator (e.g. carbon, land, material and water) focuses on a particular environmental concern (e.g. climate change, limited land, limited resources and fresh water) and quantifies resource use or waste driven by consumption[2]. The carbon footprint (CF) measures the total amount of greenhouse gas (GHG) emissions that are directly or indirectly associated with an activity or are accumulated over the life stages of a product[11–13]. When applied to a nation, the CF relates to the consumption of goods and services by final demand actors (e.g. households, governments), including GHG emissions embodied in trade[11]. The land footprint tracks the displacement of land, describing the equivalent land use required to satisfy consumption[14]. The material footprint is defined as the global allocation of used raw material extraction to the final demand of the economy[15]. The water footprint tracks the cumulative virtual water content[16] of an activity, individual, or a country, with three key components: blue water (referring to consumption of surface and ground water), green water (referring to the consumption of rain water stored in the soil as soil moisture), and grey water (referring to pollution or the volume of freshwater required to assimilate the load of pollutants)[11].

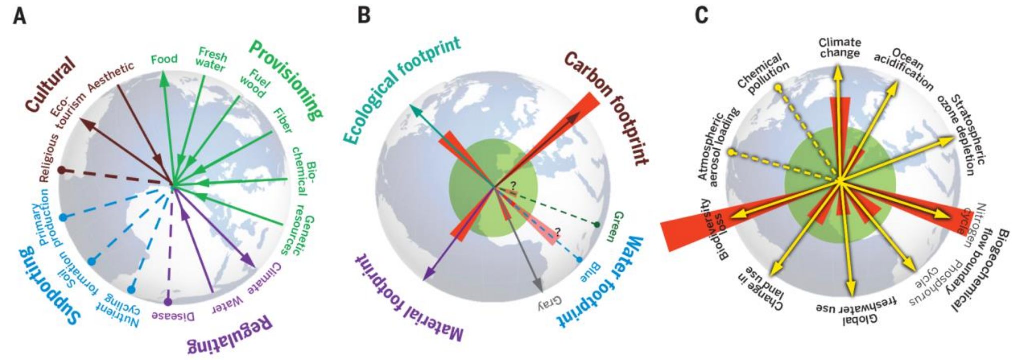

Figure 2: Examples of ecosystem services, environmental footprints, and planetary boundaries. Source: Liu et al. (2015)[7], Hoekstra and Wiedmann (2014)[2]

The frameworks of PB and environmental footprints have also been explored together, in order to bring together multiple aspects of human-nature interaction (figure 2). For each environmental footprint indicator there can be calculated a maximum sustainable level. It should be noted that adequately quantifying the level is still at its infancy[2], with proposed maximum levels being subject to large uncertainties and ambiguity (hence the ranges discussed below)[2].

A comparison between carbon, material and ecological[11] footprint, and their respective maximum sustainable footprints suggests a significant overshoot[2] (figure 2). For example, global GHG emissions in 2010 are estimated at 50.1 GtCO_2eq/year (with a 95% uncertainty range of 45.6 – 54.6 GtCO_2eq/year)[17]. This exceeds by more than a factor of two the estimated maximum sustainable level of 21 GtCO_2eq/year (range: 18 to 25 GtCO_2eq/year)[2,17]. The maximum sustainability limit here is based on scenarios with a "likely" chance of complying with the 2°C target with global emissions in 2050. Finally, the total fossil fuels resources available are significantly larger than the estimated global carbon quotas[18].

1.2. Responsibility and capacity

Additional considerations are needed to design adequate impact mitigation strategies. The problem of sharing impact mitigation effort has been largely debated[18,19], addressing perspectives of equity, economics, institutions, cooperation, and the interplay between *responsibility* (contribution to the problem) and *capacity* (ability to act). Efforts have also been made towards translating the global carbon quota to regional and national scales considering such principles of effort sharing[18].

Studies note substantial differences in the share of consumption-based impacts across countries. China, India and the United States stand out with the largest total environmental impacts contributing to 44-47% of carbon footprint[12,20], 38% of water footprint[21], 33% of land footprint[14], 41% of material footprint[15], 34% of freshwater and 41% of marine eutrophication[22]. EU27 consumption contributes to between 9%-24% of the above-mentioned global impacts, respectively[12,20,22]. The higher the environmental footprint, the higher the responsibility of that country for mitigation effort. Obviously, these differences in the spatial distribution of environmental impacts are largely driven by the distribution of human population across the planet. With population growth, the absolute resource demand of the population increases[5,23,24]. More people living on the planet means more people with needs to satisfy.

National averages of consumption-based environmental impacts per capita vary widely. For example, annual CF of 1 tCO_2eq/cap in African countries and around 30 tCO_2eq/cap in the United States and Luxembourg are noted[12]. Other environmental impacts estimated per capita have also been shown to vary widely[20]. The planetary boundaries have been "downscaled" to national equivalents[10] (figure 3), showing that countries have vastly different contributions to the environmental loads depicted on figure 2. Climate change is the most difficult per capita biophysical boundary (1.61 tCO_2eq/cap) with only 34% of countries to meet it[10].

Within countries, region-level household CF have been estimated in a single-country analyses in the context of the USA[25], Germany[26], UK[27] and China[28] among others. An analysis of urban CF, as a function of affluence and population, brings attention to the high (and rising) concentration of impacts in cities and affluent suburbs, with 200 urban areas driving 35% of global CF[29]. Finally, estimating impacts sub-nationally is key to recognizing the responsibility of elite populations within developing countries to reduce impacts[30].

Actors may also have varying capacity or ability to address mitigation. For example, the final consumer may be exempt from obligations if their activity is below a "development threshold"[19]. Some studies have combined the environmental and social perspectives (e.g. figure 3). Social outcomes can be defined and measured, e.g. following a human needs-based approach[10]. Wealthy countries have good rates of achieving social thresholds (high capacity); nevertheless, they generally report resource use far beyond the per capita biophysical boundaries (high responsibility)[10]. Ideally, a country would have blue wedges that reach the social threshold and green wedges within the biophysical boundary (figure 3). Opportunities for emerging economies to "leapfrog" over environmental degradation and opt for sustainable modes of economic and social development have been explored[30,31]. For example, high life expectancy appears to be attainable at a large range of carbon emissions, drawing attention to the "Goldemberg corner" with life expectancy over 70 years and less than 1 tCO_2eq/cap[31].

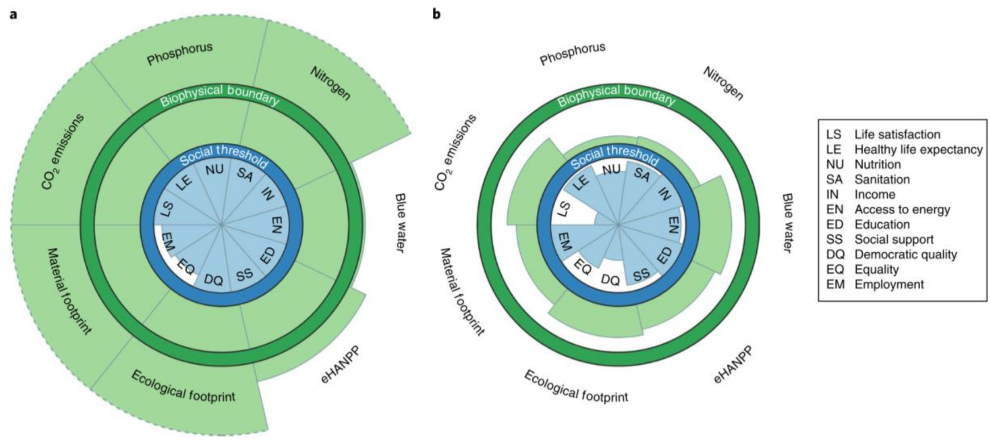

Figure 3: National performance relative to a "safe and just space" for (a) The United States, (b) Sri Lanka. Blue wedges show social performance relative to the social threshold (blue circle), whereas green wedges show resource use relative to the biophysical boundary (green circle). The blue wedges start at the center of the plot (representing the worst score achieved by any country), whereas the green wedges start at the outer edge of the blue circle (representing zero resource use). Wedges with a dashed edge extend beyond the chart area. eHANPP stands for embodied human appropriation of net primary production. Annual per capita boundaries adopted[10]. Source: O'Neill et al. (2017)[10]

There has been a substantial demand for a universal and binding political agreement between nations to limit climate change[32]. International agreements may be reached to account for the differences in responsibility and capacity for effort sharing, thus, establishing national targets and obligations (aggregated from those of their citizens[19]). National targets can then be achieved addressing the same principles on a more local level.

Finally, international trade may have significant implications for effort sharing. Trade allows for a difference between territorial- and consumption-based distribution of emissions and resource use to occur. Studies signal for the limitations of domestic climate policies focusing solely on territorial emissions, e.g. noting that the decreases of domestic emissions of Kyoto committed countries were coupled with systematic increases in the carbon intensity of imports (carbon leakage)[33,34]. In the language of responsibility, this means that the final consumer may be responsible for significant impacts taking place elsewhere. As a result, environmental burden is often displaced to developing countries[35], which arguably have lower capacity to mitigate it. Furthermore, studies have suggested that there is a systematic disadvantage for carbon-exporting economies (e.g. China, India, Eastern Europe, Middle East) in terms of socio-economic benefits[31]. At the same time, countries rarely commit to taking mitigation action beyond their borders[36], and even when they do, their commitment in terms of actual impact cuts has been questioned.

1.3. Temporal dimension

Exploring the development of environmental impacts throughout time highlights certain trends that may be useful to determine the urgency of mitigation and set expectations about the future. A recent analysis of environmental impacts shows the temporal development of total and per capita environmental impacts (table 1)[37]. The highest increase in per capita impacts is noted for material use, where the global average contribution increased from 8.3 to 11.3 from 1995 to 2011. Per capita GHG emissions, energy use, and population also increased significantly for the same period, 16%, 15%, and 22% respectively.

	UNITS	1995 (PER-CAPITA)	2011 (PER-CAPITA)	ABSOLUTE GROWTH	PER CAP GROWTH	PER GDP GROWTH
GHG emissions	t CO2 eq.	5.5	6.3	1.42	1.16	0.88
Energy use	GJ	56.0	64.4	1.41	1.15	0.87
Material use	tonnes	8.3	11.3	1.67	1.36	1.03
Blue water consumption	m3	190.6	200.1	1.28	1.05	0.80
Land use	ha	1.3	1.0	0.99	0.81	0.61
GDP (PPP)	2011int$	7,331	9,660	1.61	1.32	1.00
Population	billion	5.7	6.9	1.22	1.00	0.76

Table 1: Growth of absolute, per-capita and per-GDP environmental pressures (1995-2011). Source: Wood et al. (2018)[37]

The same study points to substantial increases in the environmental impacts displaced through international trade[37], with rising complexity of global supply chains (in line with figure 4 and Peters et al. (2011)[35]). Particularly, the share of displaced impacts grew from 24-33% for material use between 1995 and 2011, 20-24% for GHG emissions and 16-21% for energy use, respectively[37]. Other studies similarly emphasize the importance of international trade for GHG emissions[35], biodiversity[38], virtual water and water scarcity[37,39], energy, land and material use[37], and eutrophication[22]. Thus, patterns and processes at one place may increasingly enhance or compromise sustainability somewhere else (telecoupling[7]).

Significant changes in the structure of international trade also occur with rising net emission transfers from developed (figure 4, Annex B) countries to developing (figure 4, non-Annex B) countries[34,35]. This suggests a systematic displacement of impacts from the developed to the developing world. Particularly, CO_2 emissions in the developed world stabilized from 1990 to 2008 (as a result of Kyoto protocol commitments), while emissions in the developing world doubled[35]. As trade and production networks changed between 1970 and 2008, the emission hotspot locations changed as well, both inter- and intra-nationally. For example, the CF of the US has expanded most significantly in Asia (internationally) and central California, Florida, and Texas (within the country)[34].

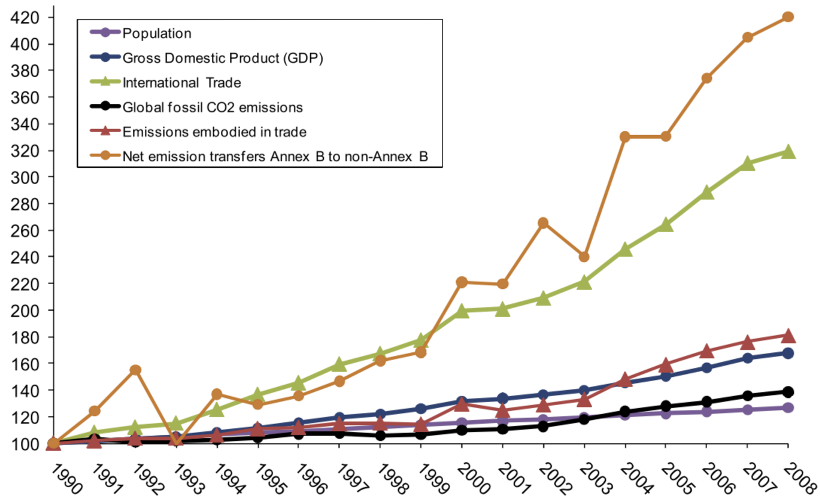

Figure 4: Development of global macro-variables indexed to 1990. Source: Peters et al. (2011)[35]

1.4. Household environmental impacts

A change in human activity for mitigation of environmental impacts can be explored at various levels including national, regional, local and household aspects. Should we call on individuals to change their behavior, or support mitigation though technological innovations, policy instruments, new markets and infrastructure? Or perhaps solutions are to emerge from the interactions among all of these[32]? This is a complex question.

Arguably, households can achieve potential impact savings through their own steps. Having accurate, accessible and actionable information may be key in enabling them to do so[40]. Research on sustainable consumption aims to understand and promote "the types of consumption behavior that are conductive for sustainable development"[41]. From the perspective of household, this means shifting to consumption patterns that exert lower pressure on the environment (within sustainable limits), while still satisfying human needs. In effect, consumption is redesigned to avoid the consumption of harmful goods (green consumption[42]), or reduce the level of consumption altogether (sufficiency[10,41]). However, strategies targeting households often give little or no priority to the impact importance of actions[40]. Even research efforts have at times focused on promoting visible (or easy) "pro-environmental" household action of little impact relevance[43]. The importance of assessing household environmental impacts for sustainable consumption, and sustainability overall, has been a main motivation for this thesis.

Furthermore, households have arguably higher agency to change their own consumption (at least in some domains), compared to changing consumption of other actors, e.g. governmental spending. In this way, the household impact perspective can be seen as enabling households to act towards sustainability. Nevertheless, the primary focus on sustainable consumption has been challenged as an approach that does not address the structural factors – the norms, rules, regulations, and institutions – vital for social transformations[32] (see sub-sections 2.4 and 2.5).

Importantly, household consumption is a major component of final demand, and thus, environmental impact associated with human activity. Following the convention of national accounts, final demand includes household, non-profit organization and government spending as well as gross capital formation, and changes in inventories and valuables in a given year[44]. Using a global multi-regional input-output (MRIO) model, prior analysis evaluated household carbon footprint (HCF) to be 72% of global GHG emissions, while that of governments and investments to be 10% and 18%[12]. Studies have quantified GHG emission contribution by final demand category and world region[12,45].

Mitigation potential associated with behavioral and infrastructural measures have been estimated in various consumption domains, e.g. buildings[46,47], transport[47], diets and manufactured products consumption[47], waste reduction[47]. Furthermore, many of these options can be achieved at a low (and even reduced) cost for consumers and little or no reduction in well-being[46,47]. The most promising targets are the ones considering both technical potential and behavioral plasticity (the proportion of households that can be persuaded to change)[46,48].

As household consumption can be linked to the majority of environmental impacts associated with human activity, addressing household consumption is key to impact mitigation. This has motivated the focus of this thesis, and the exploration of household environmental impacts (HEI) at various levels – from the macro level (country, region) to the micro (social group, household). Given the complexity of human-environment systems, the appropriate scale and locus for governance are subject to political context, social construction, geography, and institutional adaptation[49]. Prior studies have targeted and assessed HEI varying widely in method, scope and consumption detail[45]. These differences constrain direct comparisons between geographical areas and social groups, and the identification of consumption "hot-spots" from a lifecycle perspective.

2. The context of household environmental impacts

Impact assessment by itself does not suggest how to maneuver towards global sustainable consumption. Major reductions in environmental impacts would require a better understanding of the context in which HEI take place. Demand-side mitigation strategies include "targeting technology choices, consumption, behavior, lifestyles, coupled production-consumption infrastructures and systems, service provision, and associated socio-technical transitions"[50]. From a broad perspective, research on sustainable consumption encompasses the context in which consumption takes place – the power relationships, political dimensions, and governance[41].

The sections below aim to provide more detail about some of the established approaches to sustainable consumption, although this is a big challenge considering their diverse[30] and largely disconnected nature[50] across disciplines. A systems approach to HEI mitigation would require the integration of tools and understanding from various natural and social science disciplines[7,51]. Figure 5 provides an overview of key research questions and disciplines for assessing demand-side solutions.

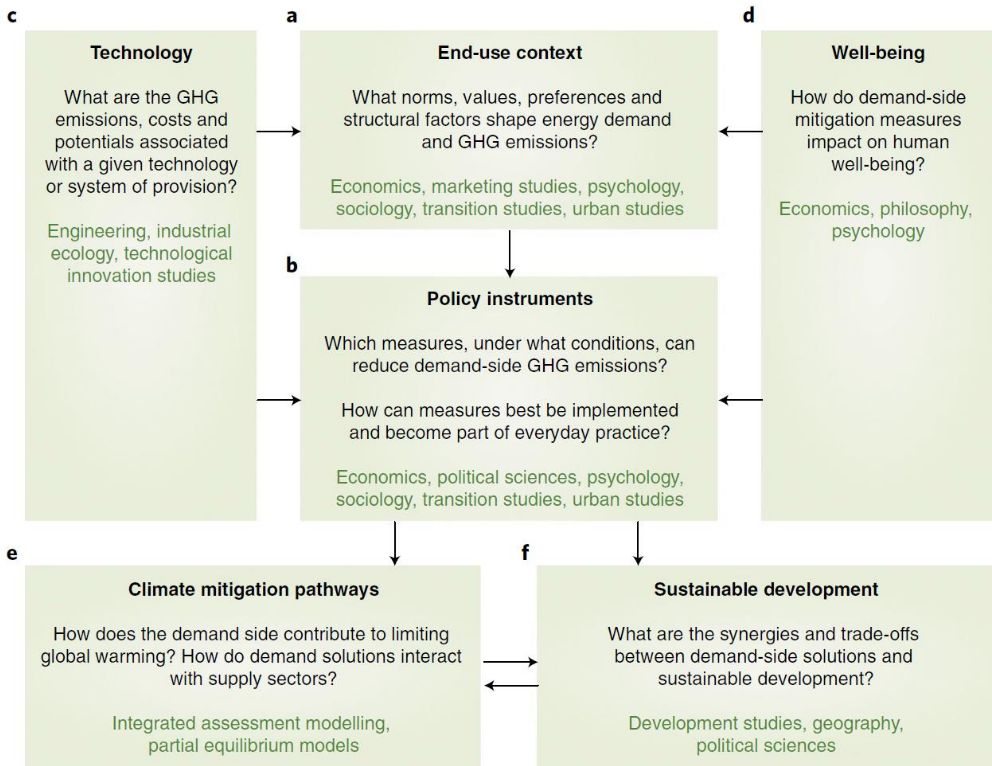

Figure 5: Key research questions and contributing disciplines for assessing demand-side solutions to mitigating climate change. Source: Creutzig et al. (2018)[50]

2.1. Technology

The technology of production or damage per unit of production has direct implications for the environmental footprint of an economic sector, individual, community, or human activity across the globe. Technological optimists find technology to provide "the only viable means by which our complex interdependent society is able to address these environmental problems"(Lynn 1989, 186)[5].

Historically, impact mitigation research and policy have focused primarily on supply-side technology solutions, e.g. encouraging energy efficiency over changing energy conservation and mobility practices[51]. The prevalent focus on technology for mitigation has been explained as potentially "easier to manage than human behavior"[5]. Industrial ecology has played an important role in the quantification of environmental degradation associated with given technologies or systems of provision from a systems and lifecycle perspective[50]. On a macro level, technological changes on environmental quality have been shown to occur in most countries independent of their economic state (at the most with a short lag before it is adopted in developing countries) and with income elasticities of less than one (rather than negative as proposed by the Environmental Kuznets Curve)[52].

Nevertheless, it has been suggested that the role of supply-side solutions to mitigate climate change is limited by rising affluence and population, off-setting behaviors (rebound effect)[53], techno-infrastructural lock-ins (where the long lifespan of urban form prolongs these effects)[47,51], controversy and importance of other environmental impacts[47]. Furthermore, there are physical limits to the rate at which new energy technologies can be deployed, even with incentives at place[54]; technical solutions also face diminishing returns in the long term with a limited potential for further diffusion[55]. Thus, a better understanding of the "social counterpart" in socio-technical systems is needed[47,50,51,55].

2.2. Human behavior

Understanding the social component around the environmental impacts is key to their mitigation. Economics and psychology have been the dominant paradigms in sustainable consumption research[41,56]. Psychologists and behavioral economists have focused on the factors and cognitive biases that shape behavior[50] with the individual as a unit of analysis. Statistically, models generally estimate elasticity of drivers of impact– estimating the change as a function of social and economic conditions[4]. Essentially, the target is the change towards pro-environmental behaviors (PEB) and lifestyles, where a change in positive "motivators" and negative "barriers" is sought as a way to encourage more people to act sustainably[56]. Policies for sustainable consumption also derive from the particular approach[57]; such perspective of impact and behavioral drivers informs about places to intervene, where impacts may be mitigated through changes in their driving forces.

This focus on the determinants of PEB have introduced the so-called "impact-behavior" gap[43]. PEB usually encompasses self-reported frequencies of various environmental behaviors[58]. A problem arises if the actual impacts of behavior are ignored, or not studied directly[43,59,60]. By measuring impact, PEB can be rated, and focus can be placed on the ones that are more relevant from impact perspective[60]. At the same time, impact studies generally do not consider attitudinal variables such as environmental concern and values, and instead focus on contextual variables (e.g. urbanity) and socio-demographics (e.g. income and household size)[58].

Determinants of PEB and impacts are discussed separately in table 2 (intent-oriented vs impact-oriented measures[61]). First, research on intent- and impact-oriented measures have progressed rather independently using different methods and explanatory variables[58]. Second, more recent studies show significant differences in the determinants of intent- and impact-oriented measures[58,60]. Third, differences in scope have been emphasized, with environmentally significant behaviors encompassing actions beyond consumer choice, e.g. citizenship behaviors such as support of environmental policies[62]. As the focus of this thesis is on impact assessment, only psychological studies that discuss both PEB and HEI are included in table 2. There are comprehensive PEB driver assessments, generally from environmental psychology, that are not depicted here, e.g.[59]. Below, a few of the relevant factors are discussed in more detail.

Studies single out income as the largest predictor of environmental impacts[25,63–66]. Rising the level of household income results in higher standards of living and provides the opportunity to increase consumption and investment[67], and the embodied environmental pressure. At the same time, nearly every government promotes economic growth, hence, reducing affluence to tackle climate change and other environmental issues is generally not an attractive target[4]. The unequal distribution of income causes vast differences in consumption-based emissions as well, with the richest 10% of the global population contributing to 34% of HCF and the poorest 50% to about 15% of the footprint[68].

Studies discuss urban form and density as key factors for mobility and shelter emissions. Cities tend to be more compact and connected, which in turn affects travel distances and the choice of transport mode[47,65]. Higher population and employment density, narrower streets and smaller city blocks, pleasant and safe urban space, mixed land uses generally promote active (walking and biking) and public transport[47]. More recent studies emphasize on the links between urban form and socio-economic factors rather than the effects in isolations[65,69]. Integrating the effects have important policy implications because of the substantial differences between urban and suburban areas in terms of lifestyles, family structures and income[69]. For example, urban cores are generally preferred by more affluent and younger adults, while suburban areas benefit from economies-of-scale effect at the household level[69]. Studies emphasize that households may cluster largely based on individual preferences for living area, e.g. with automobile-friendly neighborhoods being preferred by individuals who would rather drive[47].

	Pro-environmental behaviors (e.g. recycling)	Environmental impact (e.g. carbon footprint)
Income	Some evidence for a positive link between income and pro-environmental behavior[58]	Increasing the purchasing power of the household and thus impact[25,58,60,70]
Household size	Visible economies of scale on the PEB scale[58]	Rising household size increases the impact of the households, while generally decreasing the per capita impacts (household economies of scale)[70]; this is due to sharing common appliances, electronics dwelling area, etc., particularly in the context of housing impacts[25,58,60,63,65]
Population density/ Urban-rural typology		Living in more urban locations (urban cores rather than suburbs[25]) is associated with lower impacts due to reduced transport needs and residential energy use requirements; however, urban dwellers may have higher impacts from other categories (e.g. services)[58,69]; the importance of other urban form characteristics have also been studied[65]
Socio-demographics	Socio-demographics may also be seen as indicators or proxies for personal capabilities[61] and hence influence behavior; mixed effects on the PEB scale[58]	Generally mixed and small effects found for age, gender and education[58,60,63,65]
Dwelling size and type		Larger home size increases heating/cooling needs[25]
Vehicle ownership		Number of vehicles[25]; using public transport can lower impacts, although there may be monetary savings[66]
Motivational factors	Environmental concern significantly related to pro-environmental behavior[58]. Important lines of research include those on perceived benefits and costs, moral and normative concerns (e.g. values, norms), and affect as motivational factors for PEB[71].	Limited evidence; less importance than income and physical factors[62,65]. A strong effect of environmental concern on emissions, where the coefficient was the smallest for housing and the largest for mobility and food[58]; psychological factors can affect overall consumption levels, e.g. due to strong environmental value commitments[62]
Values	Particular values predict the tendency to behave in less cooperative ways, e.g. attaching importance to "extrinsic" values such as wealth and physical attranctiveness[72]; instead an appeal to "intrinsic" values is advocated, e.g. desire to self-knowledge, emotional intimacy and community involvement[72]	Mixed evidence Higher importance to extrinsic values associated with higher environmental footprints[72]; weaker explanatory power relative to that for behavior[60];
Self-identity	Environmental self-identity (the extent to which an individual views themselves as a person who behaves in an environmentally friendly manner) has been shown to predict various pro-environmental behaviors and to mediate the relationship between values or environmental concerns, and pro-environmental behaviors[60]	Mixed evidence No effect on carbon footprint and energy use (mismatch between environmental identity and travel impacts)[60]
Geographic location (macro level)		Size and composition of HCF varying significantly by metropolitan area (US)[70]; climatic zones of residence and dwelling insulation differences[60,66]; county-, climate- and city-specific factors[65]
Technical factors (macro level)		Carbon intensity of electricity[25];

Table 2: Pro-environmental behavior and impact drivers.

Comprehensive theories from psychology directly measure the intentional, habitual and situational influences in determining individual behavior, where intentions are believed to shape through factors such as attitudes and perceived behavioral control, as well as personal and social norms[73]. Values and environmental self-identity may strengthen awareness about environmental issues, create feelings of moral obligations to engage, and provide intrinsic rewards for action[4]. Instead, campaigns that encourage pro-environmental behaviors on the ground of financial savings may erode public commitment, reinforcing the perceived importance of extrinsic values[72].

Furthermore, social norms and interactions are considered important in mediating information and ultimately influencing normative perceptions and behavior[74,75]. Particularly, social norms can facilitate cooperation, and cause large-scale transformations of social (dis)approval and behavior[75]. Studies cover extensively psychological determinants of environmentally significant consumption and behavior[62,71]. There is mixed evidence with regards to the role of psychological factors for actual impacts[60]. Studies that adopt a combined approach show that factors such as environmental concerns, values, awareness, and moral obligations have a high explanatory power for intent-oriented proenvironmental behaviors, but a weaker power to explain variation in environmental impacts[60]. Furthermore, it has been suggested that environmental identity increases steadily with income, thus any influence of pro-environmental motivation is likely to be overridden by the "income effect"[60].

Finally, the influence of external barriers or contextual drivers is noted. Contextual factors can be of various nature including interpersonal and community influences, policy and institutional factors, incentives, techno-infrastructural factors, physical difficulty of specific actions, and various features of the broad economic, political and social context[61,71].

2.3. Social practice

Other disciplines have also contributed to advancements in sustainable consumption research, e.g. environmental sociology, political science, applied philosophy, business research, innovation studies, systems analysis, and historical studies[41].

Sociologists shift the focus from the individual behavior to every-day practices and structural issues[50], and discuss social embeddedness of individual behavior[41]. Emphasis is placed on the endogenous and emerging nature of what is referred to as external drivers or context by behaviorists[56]. Rather than autonomous agents of choice, individuals are viewed as practitioners "who routinely enact actions in accordance with shared understanding of normality and their subjective interpretation of the required forms of appropriate conduct"[57]. Theories of social practice elaborate on the emergence, persistence and disappearance of social practices (e.g. less sustainable ways of life)[56,76], where institutions, infrastructures, social networks, markets and policies interact[56,76].

Thus, rather than lifestyle choices, practices such as flying and car driving are approached as socially and culturally specific, dynamic and responding to changes in urban design and socio-technical environment[51], time and pulse of society[56], routines and the dynamics of everyday life[57], and cultural representations[57]. It is suggested that such approach avoids "making consumers the scapegoat"[42]. Increased consumption is seen as a material and cultural manifestation of a larger social context[32]. Preferences in location and transport mode are endogenous to social norms and upbringing[47]. Some policy initiatives address practices of mobility, food and shelter consumption and apply the social practice approach to policy design[56,57]. Such policy initiatives apply policy instruments targeting the re-arranging of the organization and performance of social practices and addressing the elements that coordinate them, e.g. material infrastructures and cultural representations[57].

2.4. Inertia and innovation

There is inertia associated with technologies, institutions, and behaviors, which limits transformation by a path-dependent process and inhibit innovation and competitiveness of low-impact alternatives[51]. The path dependence associated with carbon emissions to the atmosphere is termed carbon lock-in. For example, as much as 500 $GtCO_2$ is the amount of committed emissions from combustion of fossil fuels between 2010 and 2060 cumulatively if CO_2-emitting devices were allowed to live their normal lifetimes. For comparison, the estimated cumulative carbon budget for this period amounts to 900-1250 $GtCO_2$ ([17] and own calculations).

Lock-ins may be broadly categorized in three groups – techno-infrastructural, institutional and behavioral[51,77]. Infrastructural and technological lock-ins refer to the physical infrastructures that are long-lived, difficult or costly to change, e.g. buildings and urban form, carbon emitting infrastructure (coal plants, vehicles) and carbon emissions-supporting infrastructure. Cities, in particular, may be prone to lock-in due to the longevity of land-use and infrastructural decisions and "low hanging fruit" type investment[78], which obstructs impact mitigation. Institutional lock-ins refer to the "intentional and coordinated efforts to structure institutional rules, norms, and constraints"[51] of powerful economic, social and political actors, e.g. political interests, networks of relationships. Thus, there is a strong incentive for politicians and policy makers at the local, national and international levels to maintain the status quo[51], while they are also expected to respond and address the sustainability challenge.

Behavioral lock-ins can again be discussed in the context of individual and collective behaviors[51]. On the individual level, habits can exert significant influence on behavior[51,61,71,73]. Strategies to change behavior under strong habitual forces are less effective as habits exert their influence outside of conscious cognitive processing[51]. Instead, interventions that take advantage of life transitions, such as relocation or retirement, may be more effective to establish new behaviors (and habits)[51]. On the collective level, socially shared practices refer to routines and norms that coevolve with technologies, infrastructures, markets, and policies[51,76]. While dynamic in nature[57], social practices (and socio-technical systems[55]) are also path dependent and interconnected, ongoing as they are rooted in a "complex and involved network of individual cognitive processes; technology and infrastructure; and social norms, values and institutions"[51]. Durable change requires the re-ordering of multiple elements that constitute practices alongside sufficient numbers of practitioners performing these – in order for them to become normal and appropriate[57]. Lock-ins can be interdependent and mutually enforcing[51].

Positive lock-ins may also occur, where lock-ins that foster positive outcomes are encouraged[51]. Mitigation and adaptation strategies that create synergies among each other, or avoid trade-offs are thus important[78].

Innovation studies distinguish between the emergence, development and diffusion of socio-technical innovations[55,76], emphasizing on the considerable inertia that makes it difficult for innovation practices to scale up (e.g. technologies, behaviors)[41,55]. Existing systems are stabilized by the lock-in mechanisms of infrastructure, investment and behavioral patterns[77]. Moreover, existing regimes are inert in the predominant process of optimization of an inherently unsustainable system, favoring short-term performance improvements and adding to the persistency and the systemic vulnerability[79].

Transition theory emphasizes the role of group dynamics to develop niche solutions for sustainability and mainstream them into society[50,77]. For example, the multi-level perspective (MLP) framework distinguishes three levels: "niches" (the level of radical innovations), "socio-technical regimes" (stabilized on several dimensions), and "socio-technical landscape"[77]. According to MLP, radical innovations emerge in niches[76], which may be adopted more widely if external landscape developments pressures the regimes, leading to tension and windows of opportunity[77]. Social innovations such as sustainability-focused grassroots and civil society innovators may pioneer radical niche innovations as they are more willing to "think out of the box" and move beyond incremental innovations[55]. Through radical changes in consumption and production practices, such niches may overcome the aforementioned barriers to sustainability[80] and make room for alternative more sustainable ways of living.

Beyond consumption choices, a broader view on political agency captures the individual's ability to contribute to transformations by influencing structures and systems, recognizing that "individual change and collective change are, in fact, connected"[32]. Actions of committed individuals can reverse the prevailing opinion of the entire population, and thus rapid large-scale transformations can emerge from individual and local levels[32]. Sustainability transformations would depend on a broader and deeper notion of political agency that changes beliefs, values and worldviews, e.g. participating in grassroots community initiatives, and engage with sustainability solutions through art, activities, and conversations[32]. "Bottom-up" movements of revolutionary character are increasingly becoming a structural force able to co-create alternative realities largely independent from the dominant regimes[79].

2.5. Crisis or opportunity?

Tipping points refer to sudden irreversible shifts in a system state[79]. In the context of ecological thresholds and planetary boundaries, passing a tipping point might lead to an enormous impacts on the possibilities to sustain life on earth; in the context of sustainability transitions, transgressing societal tipping points is a necessary precondition to more profound systemic changes towards sustainability[79].

While the planetary boundaries do exist, the idea that they have to be seen as "limits" has been challenged[3]. Particularly, they can be seen through the lens of scarcity (with limits) or abundance (as opportunities)[3]. Thus, rather than a crisis, the sustainability challenge can be seen as the wake-up call needed for a transition to a happier, healthier and united society in harmony with nature and other life.

A better understanding of the social implications of environmental impact mitigation strategies is needed to identify potential synergies and trade-offs, as well as identify positive lock-ins to low-emission, resilient development pathways[78]. The choice of indicators for analysis and policy are important, as they emphasize the aspects that should be encouraged[42]. Government attention on social well-being measures should be integrated in national planning[42], with only 25% of countries report life satisfaction above the "safe and just" social threshold (6.5 on 0-10 Cantril ladder scale)[10]. Opportunities to enhance well-being, while reducing environmental impacts, shall also be explored[41,50]. There is also focus on the link between HEI and time use, emphasizing the importance of time prosperity and work-life balance[65]. A key research and policy challenge is to systematically assess both benefits and costs of demand-side mitigation strategies[50].

The policy instruments to enable demand-side solutions are largely debated and different disciplines offer various perspectives on the matter[50], including e.g. regulations and other command-and-control types of measures[81]; carbon taxation and financial incentives[81]; choice editing[42] and "nudges"[50]; phasing out of impact-intensive goods and infrastructure[42,50,51] and improving physical and social provisioning system[10]; (intrinsic) motivation targeting[82]; social norm, social sanctioning and changes in the visibility of behavior[75]; encouraging grassroots innovation and building communities[42]; positive lock-in and synergies between mitigation and adaptation strategies[78]; network governance and interaction with multiple stakeholder groups[81]. The need for policy framing to go beyond green consumerism and reflect on the institutional, structural and cultural determinants of consumption has also been emphasized[42]. The most effective interventions typically combine policy tools and approaches and address multiple targets[46].

3. Thesis contribution

3.1. Research questions

While some literature exploring environmental impacts of household consumption existed prior to this thesis, there is a need to explore household embodied impacts systematically and in further detail due to the known large importance of household GHG emissions[45].

First, there is a need to explore the implications of household consumption on various environmental indicators (footprints) simultaneously. Analysis focusing on a single indicator may be vulnerable to trade-offs and unforeseen damage. Instead, analysis from a multi-indicator perspective would allow for a more informed decision-making, and create awareness about potential co-benefits with regards to other indicators. Furthermore, the lifecycle perspective is necessary to provide an environmentally relevant context (e.g.[30]).

Second, various stakeholders may act towards impact mitigation, provided that they have actionable information to do so. Therefore, analysis of household environmental impacts from different perspectives (from the macro to the micro level) may be useful to different stakeholders and decision makers (civil society, policy makers, and industry actors). For example, HEI country averages may be useful for national and international policy, while more detail and context may be important for the assessment of impacts of an individual household or the design of adequate actions in a specific region. A shift beyond national averages is needed to observe the distribution of environmental impacts (responsibility), and potentially enable an equitable distribution of mitigation. National targets may be allocated to region-specific targets and plans to implement them[83]; however, when no CBA perspective is available, the focus on territorial impacts may lead to carbon leakage.

Third, it is crucial to highlight the importance of HEI embodied in international trade. The origin of emissions and resource use is of high relevance for impact mitigation, as well as the ethical concerns around impact displacement. Furthermore, an assessment of both "direct" and "indirect" environmental impacts is needed, encompassing the impacts embodied in global supply chains, which are of growing importance with increasing international trade. Bringing attention to "indirect" impacts is also crucial for making such impacts more visible to decision makers and final consumers.

Lastly, it is crucial to trace consumption impacts to products and consumption categories in order to get an overview of the "hot spots" of consumption, and essentially inform the re-design of consumption. Such an overview would also encourage mitigation in consumption domains that are more relevant in terms of totality of impacts, rather than focusing efforts towards changing consumption in low-impact domains.

These considerations and "gaps" in the literature lead to the following research question, addressed differently by the primary articles in this thesis:

Q1. What are the environmental impacts associated with household consumption?

- What are the environmental impacts across nations and environmental indicators? What are the impacts embodied in international trade? What is the contribution of various consumption categories for total impacts? [Article 1]
- What is the distribution of environmental impacts across regions in EU countries? What is the subnational distribution in impacts across consumption categories? [Article 2]
- What is the carbon contribution of individuals in domains of high consumer lock-in? [Article 3]
- How effective are sustainability-focused grassroots initiative members in reducing their carbon footprints? [Article 4]

The thesis further aims to contribute to the understanding of underlying relationships between environmental footprints and various socio-economic, geographic and technical factors, as well as other social indicators (e.g. well-being). Beyond quantifying HEI, the goal of this thesis (and more broadly the GLAMURS project) is to aspire a change towards more sustainable ways of consuming and living, beyond technological shifts. Similar to the impact assessment, a good understanding of the context for HEI mitigation is needed at various complementary levels (e.g. national and regional, social and individual).

Q2. What is the context in which household environmental impacts take place, and what are potential strategies to mitigate impact?

- What changes in HEI are expected with rising spending in various consumption categories? [Article 1]
- Can the observed regional variation in household carbon footprints be explained by various socio-economic, geographic and technical factors? What are important factors for total footprints and by consumption category? [Article 2]

- What behavioral, socio-economic and structural factors shape consumption and its carbon intensity in domains of high carbon lock-in? What are the implications for mitigation strategies? [Article 3]
- How do grassroots initiative members compare to their regional counterparts in terms of well-being and importance of socio-economic factors? [Article 4]

3.2. Articles

In **Article 1** [A1 appended], we provide a global assessment of household environmental impacts. Four footprint indicators are adopted, particularly, carbon, land, water and material footprints using the EXIOBASE 2.2 database. We highlight the importance of environmental pressure arising from households with their consumption contributing to more than 60% of global GHG emissions and between 50% and 80% of total land, material and water use. We quantify and compare total and per capita household impacts across countries in 2007. In terms of carbon, United States (18.6 tCO_2eq/cap), Luxembourg (18.5 tCO_2eq/cap) and Australia (17.7 tCO_2eq/cap) contribute to more than 5 times the world average (3.4 tCO_2eq/cap), and more than 10 times the per-capita contribution of Indonesia (1.3 tCO_2eq/cap) and India (0.8 tCO_2eq/cap). Similarly, the per capita resource consumption varies widely across countries in terms of land, material and water resources with a world average of 0.01 km^2, 5 t and 210 m^3, respectively. The footprints are unevenly distributed across world regions, with wealthier countries generating most significant impacts per capita. Furthermore, we break down HEI in terms of nature (direct vs indirect), origin (imported vs domestic) and consumption category (food, mobility, shelter, clothing, manufactured products and services). Globally, about 20% of household emissions, and only 5% of household water use, are direct. Thus, the majority of HEI are indirect or embodied in consumer goods. A significant portion of the indirect emissions and resource use are embodied in international trade, with substantial impacts in imports from the developing countries. The distribution of HEI in terms of domestic and imported impacts also varies largely across countries, e.g. with a share of imported impacts between 8-65% for carbon, 2-99% for land, 8-98% for materials, and 2-99% for water across countries. Mobility, shelter and food are the most important consumption categories across the environmental footprints. Though their environmental relevance varies across footprint indicators, the three categories consistently make up between 55% and 78% of the total HEI. Globally, food accounts for 48% and 70% of household impacts on land and water resources, respectively. Clothing contributes to a much lower share of impacts, between 3% (for carbon, land and water) and 5% (for materials), globally. Shelter and mobility stand out with high carbon and material intensity, whereas the significance of services for footprints relates to the large amount of household expenditure associated with them. Mobility has the largest carbon multiplier in EU context, close to 3.5 $kgCO_2eq$/EUR and, consequently, the largest footprint contribution (27%) out of all consumption categories. Finally, we explore expenditure elasticities across environmental indicators and consumption categories. Elasticities suggest a positive and significant relationship between household spending and their environmental impacts, with an elasticity coefficient varying between 0.40 for water and 0.66 for carbon. Furthermore, lower coefficients are noted for basic consumption categories such as food and shelter, suggesting a shift of consumption towards non-primary consumption items.

In **Article 2** [A2 appended], we provide a regionalized consumption-based GHG emission inventory based on 177 regions within the European Union. Thus, combining consumer expenditure surveys and EXIOBASE 2.3, we provide a higher spatial detail than prior cross-country assessments and make a key contribution for the incorporation of CBA in local decision-making. While the EU Commission has encouraged to combine national and international carbon mitigation measures with subnational policies and targets, prior to this analysis there has been little harmonized effort towards the quantification of impacts within EU countries. The top emission decile includes regions with average HCF of 22-16 tCO_2eq/cap, while the bottom decile contributes to 5-7 tCO_2eq/cap. We evaluate the within-country inequality of HCF, highlighting the substantial subnational ranges varying widely between 0.6 and 6.5 tCO2eq/cap. The significant differences in regional contribution in terms of total and per capita impacts suggest notable differences in terms of climate change responsibility. The absolute and relative importance of consumption categories varies widely across regions. Transport, food emissions range between 13-44%, 11-32% and 10-46% across EU regions, respectively. We further explore factors that may explain some of these regional differences, namely, socio-economic (income, household size, urban-rural typology, level of education), geographic (temperature, resource availability) and technical factors (carbon intensity of the local electricity mix). The lack of cross-national region-level studies has so far prevented analysts from drawing broader policy conclusions that hold beyond national and regional borders. Income is singled out as the most important driver for a region's HCF explaining 29% of the variation in total HCF, although its explanatory power varies across consumption categories. The income-footprint relationship is of concave nature with a thousand-EUR rise in income results in roughly 450, 300 and 150 $kgCO_2eq$/cap increase in HCF at the 25th, 50th and 75th income percentile of the regional sample, respectively. The consumption categories of clothing, mobility and manufactured products appear particularly income elastic. Increasing the average household size of a region by one person leads to a drop in the average person's emissions associated with electricity and housing fuels (750 $kgCO_2eq$/cap) and waste treatment (80 $kgCO_2eq$/cap). Socio-economic factors such as household size, education, dwelling size and basic consumption generally explain between 11%-44% of the subnational heterogeneity in HCF. Furthermore, heating degree days have a positive and significant impact on shelter emissions explaining 30% of the variation, while the electricity intensity mix explains an additional 23% of the variation. An overview of other environmental footprints (land, materials and water) is also made available elsewhere (https://www.environmentalfootprints.org/regional).

In **Article 3** [A3 appended], we calculate individual-based carbon footprints to explore mitigation potential in high-impact domains of housing and mobility, characterized by high structural constraints. Scientists and policy makers increasingly call for demand-side solutions for mitigating climate change, however, targeting individual action in the context of systematic barriers can be rather challenging. Furthermore, most research effort focuses on either the physical dimension or the social dimension, while a more integrated approach may more adequately address mitigation. We utilize a survey on consumer behavioral, attitudinal, contextual and socio-demographic factors in four different EU regions. For land-based mobility, our sample has an average annual travelled distance of 9,500 km and carbon intensity of travel varying between 3 and 225 grCO_2eq/km for active and private motorized travel, respectively. On average, the CF of mobility is 1.5 and 2.4 tCO_2eq/cap for land- and air-based mobility, even though only 40% of our sample travel by air. Based on observed differences in mobility carbon footprints across households, we find that the key determining element to reduced emissions is settlement density, while car ownership, rising income and long distances are associated with higher mobility footprints. Thus, even at high settlement density, HCF can vary widely (e.g. between 0.2 and 1.5 tCO_2eq/cap under considered cases) due to differences in car use and distance as well as underutilization of mobility-sharing initiatives. There remains a strong need for incentives to reduce air travel. For shelter, the annual carbon contribution of electricity use at home, space heating and water heating is 1.0, 1.1 and 0.2 tCO_2eq/cap, respectively. Our results indicate that changes in dwelling standards and larger household sizes may reduce energy needs and the reliance on fossil fuels. Significant reductions in shelter HCF may occur in both urban and rural context, provided that significant factors are explored together. We discuss the role of policy in overcoming structural barriers in domains where consumers as individuals have limited agency. For mobility, this includes reducing short- and long-distance travel distance (e.g. urban connectivity, telecommuting, and infrastructural improvements) and the carbon intensity of travel (e.g. active travel, carpooling, incentives for car sharing rather than ownership), incentives to reduce air travel. For shelter, this includes incentives to reduce energy use (e.g. dwelling standards and multi-household living) and its carbon intensity (e.g. regulations and financial incentives).

In **Article 4** [A4 appended], we calculate the carbon footprint of sustainability-focused grassroots members and compare their contribution to that of their socio-economic counterparts living in the same regions (control group). Sustainability-oriented grassroots initiatives emerge bottom-up to create opportunities for lifestyle changes and previous research indicates that initiatives play a role in the sustainability transitions. Yet, no prior assessment has ascertained the efficacy of their members to reduce carbon emissions, while exploring implications for well-being and income-footprint relationship. We analyze the CF of 141 members of various sustainability-focused grassroots initiatives located in several EU regions. On average, initiative members have 17% lower average CF relative to non-members, with 7.8 versus 9.3 tCO2eq/cap. We evaluate inter-group differences across consumption domains, finding that grassroots initiative members have 43% lower carbon footprints (CF) for food and 86% for clothing compared to their regional socio-economic and demographic counterparts. Yet we find no significant differences in the CF of housing and transport. Our analysis on the importance of the income variable for initiative members suggests that increases in income are not associated with increases in the total CF of members. In terms of consumption and behavior, for initiative members, higher income does not imply higher expenditure on food, clothing and electricity, or higher car ownership and increased travel. Instead, factors such as age, household size, and gender better explain the variation in the CF of initiative members. At the same time, the importance of income is confirmed for the CF of non-members. Finally, members show higher life satisfaction compared to non-members and are 11-13% more likely to evaluate their life positively. Initiative members are also 7-9% less likely to evaluate their life negatively by disagreeing with life satisfaction statements. Our findings suggest that lower consumption-based impacts and higher well-being are compatible for members of grassroots initiatives. Further efforts are still required to reach sustainable consumption levels per capita. Regardless, we consider such initiatives worthy of research and policy considerations as a strategy for sustainability transformation.

4. Discussion and conclusions

This thesis contributes to the quantification of HEI at various levels, from analyzing consumption of countries and regions, to that of individuals and communities. It signals for the wide variations on a per capita basis, particularly explained by differences in spending and affluence. Different countries (A1), regions (A2), social groups and individuals (A3, A4) have different contribution to environmental impacts. The provision of an adequate HEI assessment contributes to the monitoring and management of consumption-based impacts at various scales and to the debate on sharing impact mitigation effort across the population. The overview of HEI by consumption category further puts impacts into perspective, allowing for a prioritization of action (A1-A4). Furthermore, the parallel analysis by consumption category enables to evaluate the consistency of behavior (A3, A4).

Having a macro-perspective on the distribution across countries and regions may enable a more equitable distribution of the mitigation challenge (A1, A2). The origin of products can be traced to avoid significant displacement of impacts to other areas, particularly, more vulnerable ones. Furthermore, regions systematically focus on mitigation of impacts occurring on their territory, e.g. by deciding on waste treatment options or transport planning. A consumption-based inventory of GHG emissions and resource use is, thus, needed to complement local decision-making (A2). Consumption-based policies may be effective to sustain regional and national competitiveness and limit the opportunity for carbon leakage (A1, A2).

Micro-perspectives on the HEI of various social groups may be useful for profiling and the identification of synergies and strategies for sustainability transitions. For example, sustainability-focused grassroots initiatives emerge as bottom-up social innovations that aim to overcome barriers to sustainability. HEI assessments of such niches may be useful to evaluate their potential for impact mitigation and enhancement of well-being (A4).

This thesis emphasizes the importance of integrating environmental and social impact in the redesign of consumption (A1, A2 and A4). Systems integration is key to model impacts and future trends, and develop demand-side solutions. Shifts in consumption from one category to another may reduce impacts in terms of one indicator, but often at an increased impacts of another indicator (A1). The aim is to make such trade-offs more visible and accountable in decision making. Assessing the influence of consumption changes on life satisfaction and other social indicators may uncover a potential for co-benefits (A4).

Furthermore, micro-perspective on the differences among households and social groups within a certain region may shed light on the differences in the context in which consumption takes place and allow for different strategies to target environmental impacts (A3, A4). For example, policies that target changes in time-use (e.g. tele-working) and urban design (e.g. compact cities) may have significant influence on the impacts taking place (A3). The interaction and co-development of factors shaping HEI is import for real-life decision-making and prospective planning (A3), e.g. the tendency of younger, richer and smaller households to inhabit urban cores[69].

4.1. Policy implications

It is crucial to implement a comprehensive package of policies for impact mitigation enabling various stakeholder engagement and considering differences in the geographical scope, technical infrastructure, socio-economic context, social and cultural aspects[84]. Policy instruments may need to address the local context, e.g. a region or a social group, in order to effectively mitigate environmental impacts or enhance social well-being.

Different disciplines have offered various policy instruments to encourage more sustainable ways of living[85]. HEI assessments (A1-A3) may inform regulation, incentive[81], and nudging[50] approaches about the most harmful and impact-intensive consumption products and domains. HEI feedback may further be useful in information schemes and the re-design of consumption, e.g. to avoid substantial rebound[86]. Identifying and encouraging positive lock-ins[78] through changes, for example, in urban design, shared mobility and dwelling standards may be key mitigation strategies (A3).

Policy measures may be costly and short-lasting if they miss to address the deep social structures, values, norms, and worldviews[32]. Policy frameworks that enable a deeper social transformation, and encourage new social norms and credible modes of co-production, collaboration, and sharing (A4) may offer more long-term benefits[41,75]. For example, re-establishing social connectedness and the connection with nature may also be important for sustainable consumption and happy people (A4). It is important to recognize the complexity of the sustainability challenge, and the social, technical, institutional, political, and economic systems that interact.

Our analysis highlights the importance of both top-down and bottom-up interventions for sustainability transformations (A1-A4). Bottom-up action such as lifestyle changes and initiative engagement may be particularly successful in consumption domains of attainable consumer change, where low-impact social norms and new consumption cultures can be encouraged[84]. Top-down intervention may be more appropriate in domains of higher consumer lock-in, where various incentives, nudges, regulations, and infrastructural changes may be needed for substantial cuts in HEI. Cooperation and interaction among multiple stakeholders may also be key[81] for a lasting and systematic transformation.

4.2. Further research advancements

There is a need for a transdisciplinary approach that integrates demand-side solutions, assesses mitigation potential and implications for social well-being, and provides an action plan[50] for civil society, policy makers, market actors and various other stakeholders. Exploring these in a cross-country analysis framework may bring important insights about the varying context and relevant effects, which currently constitutes an important research gap.

Further attention is needed on policies targeting displaced impacts (A1) in accordance with the principles of responsibility, transparency and sustainability, under the limited legal power that countries can exercise on global level[41]. How can different stakeholders collaborate decarbonize local and global supply chains in consideration of these principles is key. Furthermore, localizing production may increase the visibility and manageability of HEI and encourage production and consumption practices to adapt. Studying the interplay between such adaptation effect and the efficiency gains achieved through trade may have important implications for HEI mitigation.

Contextual considerations are needed for the provision of adequate mitigation strategies for various stakeholders. Further advancements are needed for the translation of HEI information into action. Prescriptive and normative measures to tackle sustainability may fail to properly recognize the circumstances of various stakeholders and hence risk unintended consequences.

With regards to the sustainability-focused grassroots initiatives, further investigation is needed to discuss impact mitigation potential, rising questions about up-scalability and scope. Quantifying multi-level, multi-criteria, and long-term effects of initiatives is a challenge for future research in this area.

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Appendix A.

Article I

Environmental Impact Assessment of Household Consumption

Diana Ivanova*, Konstantin Stadler, Kjartan Steen-Olsen, Richard Wood, Gibran Vita, Arnold Tukker and Edgar G. Hertwich.

Supplementary materials can be found online at:

https://onlinelibrary.wiley.com/doi/abs/10.1111/jiec.12371

Volume 20, Issue 3, Pages 526-536, DOI: 10.1111/jiec.12371

Environmental Impact Assessment of Household Consumption

Diana Ivanova, Konstantin Stadler, Kjartan Steen-Olsen, Richard Wood, Gibran Vita, Arnold Tukker, and Edgar G. Hertwich

Keywords:

environmentally extended multiregional input-output (EE-MRIO) analysis
expenditure elasticity
footprint analysis
household environmental impacts
industrial ecology
regression analysis

Supporting information is available on the *JIE* Web site

Summary

We analyze the environmental impact of household consumption in terms of the material, water, and land-use requirements, as well as greenhouse gas (GHG) emissions, associated with the production and use of products and services consumed by these households. Using the new EXIOBASE 2.2 multiregional input-output database, which describes the world economy at the detail of 43 countries, five rest-of-the-world regions, and 200 product sectors, we are able to trace the origin of the products consumed by households and represent global supply chains for 2007. We highlight the importance of environmental pressure arising from households with their consumption contributing to more than 60% of global GHG emissions and between 50% and 80% of total land, material, and water use. The footprints are unevenly distributed across regions, with wealthier countries generating the most significant impacts per capita. Elasticities suggest a robust and significant relationship between households' expenditure and their environmental impacts, driven by a rising demand of nonprimary consumption items. Mobility, shelter, and food are the most important consumption categories across the environmental footprints. Globally, food accounts for 48% and 70% of household impacts on land and water resources, respectively, with consumption of meat, dairy, and processed food rising fast with income. Shelter and mobility stand out with high carbon and material intensity, whereas the significance of services for footprints relates to the large amount of household expenditure associated with them.

Introduction

Scientists have investigated the resource use required to support household consumption in an effort to understand the relationship between humans and nature (Wackernagel and Rees 1996; Fischer-Kowalski et al. 2014; Herendeen and Tanaka 1976). They have investigated the emissions caused by the production, use, and disposal of products in final use to target efforts to reduce environmental impacts and assess trade-offs (Dietz et al. 2009; Hertwich 2011; Tukker et al. 2010). Traditionally, the analysis of household environmental impacts was based on national statistics and production systems, treating imported goods as if they had been produced in the country where they are consumed (Lenzen et al. 2006; Hertwich 2011; Tukker and Jansen 2006). The energy and emissions intensities of products produced in different countries can be quite different, reflecting a combination of differences in the structure and efficiency of economies and in the product mix being produced. Including the technology of important trade partners as proxies for imports to Norway, Peters and Hertwich (2006) demonstrated a striking impact of technology differences: The foreign production of products consumed by Norwegian households accounted for 13 million tonnes carbon dioxide (CO_2), whereas using domestic production as a proxy would give only 5 million tonnes. Weber and Matthews (2008) found significant effects also for the United States, which is less trade exposed. As a result, global

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DOI: 10.1111/jiec.12371

Editor managing review: Kuishuang Feng

Volume 20, Number 3

multiregional input-output (MRIO) models were developed to trace the environmental impacts associated with consumption. Hertwich and Peters (2009) provided the first analysis of the carbon footprint of different nations, identifying the role of households, public consumption, and investments, and specifying the role of different consumption categories as a function of income. These calculations have been reproduced and updated (Davis and Caldeira 2010) and extended to other pollutants, materials, land use, and water consumption (Wiedmann et al. 2015; Kanemoto et al. 2014; Steen-Olsen et al. 2012). In recent work, however, consumption is addressed more broadly, not focusing on understanding households, but rather looking at entire nations.

In this article, we analyze the environmental impact of household consumption of different countries in terms of the material, water, and land-use requirements, as well as greenhouse gas (GHG) emissions, associated with the production and use of products and services consumed by these households. We do so using the newly established EXIOBASE 2.2 MRIO database, which describes the world economy in 2007 consisting of 43 countries, five rest-of-the-world (RoW) regions, and 200 product sectors (Wood et al. 2015). The land footprint reported here is an unweighted land use as opposed to the productivity weighting applied by Wackernagel and Rees (1996). The other indicators are water footprint (Hoekstra 2003), carbon footprint (Wiedmann and Minx 2008), and material footprint (Wiedmann et al. 2010). The concept of footprint family has been tested against criteria such as policy relevance, indicator coverage, and their complementary properties (Galli et al. 2012).

The motivation behind the recent focus on national footprints is the importance of emissions embodied in international trade to climate policy (Wyckoff and Roop 1994; Munksgaard and Pedersen 2001; Peters and Hertwich 2008). Time series of national carbon footprints show that increasing imports from developing countries have contributed significantly to the continued rise of the national carbon footprint of developed countries, even though many of these countries have managed to stabilize and even reduce their territorial GHG emissions (Kanemoto et al. 2014; Peters et al. 2011). Whereas the national focus is appropriate for national and international policy making, an understanding of household footprints can provide insights into the social determinants of environmental impacts and can inform household actions directed toward reducing footprints. Household consumption has a strong relation with consumer behavior, lifestyles, and daily routines and a potential resistance to change owing to social and cultural embeddedness (Caeiro et al. 2012). Households have a relatively large degree of control over their consumption, but they often lack accurate and actionable information on how to improve their own environmental performance (Gardner and Stern 2008), and household footprint calculations can provide such information.

The novelty of our study is that it uses an integrated methodological framework across the set of footprint indicators to evaluate household environmental performance based on a database with a higher level of environmental detail. This integrative approach allows us to assess and compare environmental impacts of household consumption across indicators, regions, and consumption categories directly and with lower uncertainty. It can further be used to identify where mitigation of certain impacts, for example, emission reductions, would come at the expense of other impact categories, such as higher levels of water, land, and material consumption (Tukker et al. 2013).

Methods and Data

Household environmental impacts are derived from an environmentally extended MRIO (EE-MRIO) model constructed using the high-resolution EXIOBASE database (Wood et al. 2015). The core of the model is an input-output table representing the flow of goods and services throughout the global economy for the reference year 2007. All emissions and resources required for the production of output are allocated to goods and services purchased by final consumers (Hertwich 2011).

The analysis is based on version 2.2 of EXIOBASE, which features a higher level of detail on environmentally relevant sectors (e.g., agriculture, energy, and manufacturing) and environmental extensions (e.g., emissions, resource use, and pollutants) in comparison to other MRIO databases (Wood et al. 2015). EXIOBASE has a major advantage in providing much greater product disaggregation (200 product sectors) in an integrated framework within the system of environmental-economic accounting guidelines. It accommodates information about 43 countries, which, together, account for approximately 89% of global gross domestic product (GDP) and between 80% and 90% of the trade flow by value within Europe (Stadler et al. 2014). The MRIO table is supplemented with information on the environmental load intensities of economic sectors. Economic accounts were coupled with data on resource use and emissions sourced from databases with information on primary resource extractions, emission factors and activity variables, and agricultural and forestry activities (Food and Agriculture Organization of the United Nations Statistics Division, the International Energy Agency database, and so on) (Tukker et al. 2013).

The global warming potential (GWP) metric is used to convert greenhouse gases (CO_2, methane, nitrous oxide, and sulfur hexafluoride) to equivalent amounts of CO_2 by weighting their radiative properties for a time horizon of 100 years. Land use reflects use of cropland, pasture land, and forest land. The material footprint relocates the domestic extraction of raw materials (primary crops, crop residues, fodder crops, grazing, wood, aquatic animals, metal ores, nonmetallic minerals, and fossil fuels) from production to consumption in a mutually exclusive way, including only materials that are directly used by an economy. Our water footprint indicator includes blue (fresh surface and groundwater) water consumption embodied in agriculture and livestock products, manufactured products, electricity, and direct demand from households. The national environmental footprint is calculated as a function of the footprint multiplier, capturing the intensity of household purchases (e.g., amount of GHG emissions per euro [EUR] of household expenditure), and the product quantity demanded in monetary terms.

Table 1 Environmental impact by final demand category

	Carbon footprint	*Land footprint*	*Material footprint*	*Water footprint*
Households	65 ± 7%	70 ± 11%	51 ± 8%	81 ± 7%
NPISH	1 ± 1%	1 ± 1%	1 ± 1%	1 ± 1%
Governments	7 ± 3%	5 ± 3%	7 ± 3%	5 ± 3%
Gross capital formation	24 ± 7%	19 ± 10%	37 ± 9%	10 ± 6%
Changes in inventories	3 ± 2%	5 ± 5%	4 ± 3%	3 ± 2%

Note: The mean and standard deviation estimates respond to the sample of 43 countries included in the EXIOBASE with the deviation caused by the different distribution of final demand categories across countries. Environmentally relevant requirements are linked to final demand by households, nonprofit institutions serving households (NPISH), governments, gross capital formation, and changes in inventories. Changes in inventories occur when prices prevailing when goods are withdrawn differ from prices when production takes place (SNA 2008).

Following the convention of national accounts, final demand is the estimate obtained by summing household, nonprofit organization, and government spending as well as capital formation and changes in inventories and valuables in a given year (SNA 2008). In order to isolate the environmental impacts of households, we only take into account household expenditure across product sectors. This approach allows us to estimate the magnitude of indirect GHG emissions and resource use embodied in the global supply chains of household purchases subject to certain limitations discussed later.

In addition, households generate environmental stress directly through their use of some products, for example, when driving or using fuel to heat their homes. In EXIOBASE, household direct impacts are aggregated into a total for each region. We distribute direct carbon emissions between personal transport and residential fuel use following the GTAP 7 database (Lee 2008). Using GTAP, we allocated CO_2 emissions from coal, crude oil, and gas to housing (i.e., shelter) and those from petroleum products to transport. Direct water use was allocated to shelter under the consideration of previous observations (see Vewin 2012; Vickers 2001; EEA 2001). Direct noncommercial use of land and materials by households was neglected.

Finally, by applying the concept of expenditure elasticity, we are able to evaluate changes in the environmental footprints resulting from changes in household expenditure (Baiocchi et al. 2010; Kerkhof et al. 2009; Weber and Matthews 2008). Household expenditure elasticity, ε, measures the percentage change in the quantity of environmental impacts with respect to a 1% rise in the total household demand (measured in monetary units) (equation 1):

$$\varepsilon_i = (\partial f_i / \partial y)/(f_i / y) \tag{1}$$

where y represents per capita yearly expenditure and f represents per capita footprint for each of the footprint indicators i. Model (1) can be transformed using natural logarithm transformation resulting in a set of univariate regressions for each footprint indicator, where a and ε are constants and u is the error term (equation 2):

$$\ln f_i = a_i + \varepsilon_i \ln y + u_i \tag{2}$$

Results

Carbon Footprint

The global carbon footprint associated with household consumption in 2007 was 22 gigatonnes (Gt) carbon dioxide equivalent (CO_2-eq) including direct impacts and impacts embodied in household purchases. This amounts to 65% of the total emissions generated that year. The average allocation of environmental impacts across final demand categories is presented in table 1. GHG emissions were unevenly distributed across regions with households in four major economies, namely, the United States, China, Japan, and Russia, contributing to roughly half of the global impacts from household consumption. Households in the United States alone contributed to a quarter of global emissions, or 5.6 Gt CO_2-eq. The most significant contribution is from the consumption of energy-intensive services and electricity produced from coal. The household carbon footprint of the European Union (EU) amounted to 4.9 Gt CO_2-eq.

On a per capita basis, carbon footprints of households vary widely (figure 1). The United States contributes to 18.6 tonnes (t) CO_2 per capita (CO_2-eq/cap). The world average is 3.4 t CO_2-eq/cap, suggesting a 5.5-factor difference. In terms of the total final demand, the United States contributes to 4.9 times higher GHG emissions than the world average from a consumption perspective and to only 3.9 times higher emissions from a production perspective. Thus, the United States are a net importer of GHG embodied in traded goods, largely owing to household consumption, 74% of the country's final demand.

A strong positive correlation between GDP per capita based on purchasing power parity (PPP) and per capita carbon footprints is signaled by the correlation coefficient of 0.87. Several Western economies, such as Sweden (8.7 t CO_2-eq/cap), France (8.8 t CO_2-eq/cap), and Japan (9.0 t CO_2-eq/cap) stand out with lower impacts than countries with similar income related to the prevalence of nuclear and hydro power (EEA 2013). Hence, a significant portion of household impacts from Sweden and France are embodied in imports, 65% and 51%, respectively (figure 2), owing to their higher carbon intensity compared to domestic production.

The distribution of GHG emissions from household activity on domestic goods and imports varies largely across countries.

Countries	Carbon Footprint(tCO_2-eq)	Land Footprint (1000 m^2)	Material Footprint (t)	Water Footprint (m^3)
World average	3.4	10.0	4.9	209
Austria	11.3	18.1	17.4	298
Belgium	12.2	28.1	17.8	492
Bulgaria	5.4	6.9	8.1	182
Cyprus	10.9	9.2	12.4	278
Czech Republic	9.4	9.2	11.8	174
Germany	11.9	20.0	16.0	347
Denmark	12.2	20.9	16.8	453
Estonia	10.9	20.9	15.6	258
Spain	8.1	21.0	14.2	561
Finland	13.6	27.4	17.9	304
France	8.8	22.3	14.2	396
Greece	13.4	26.9	18.3	700
Hungary	5.9	8.2	7.3	194
Ireland	12.9	22.1	17.1	297
Italy	9.6	19.1	13.6	407
Lithuania	6.5	12.5	9.1	180
Luxembourg	18.5	44.4	27.6	816
Latvia	6.2	22.9	10.8	181
Malta	9.2	14.9	14.8	628
Netherlands	11.8	35.5	17.2	575
Poland	7.8	9.2	10.3	130
Portugal	6.8	18.0	11.5	509
Romania	4.6	9.4	12.2	325
Sweden	8.7	18.8	15.7	322
Slovenia	10.1	20.2	13.4	262
Slovakia	8.3	14.5	11.9	287
United Kingdom	13.3	21.9	17.9	456
United States	18.6	23.0	18.4	651
Japan	9.0	11.2	9.2	290
China	1.8	5.4	3.1	130
Canada	14.6	40.6	18.1	510
South Korea	8.7	13.8	10.4	340
Brazil	1.8	22.0	8.2	159
India	0.8	2.1	2.0	261
Mexico	3.8	16.6	5.9	277
Russia	7.6	69.6	9.3	331
Australia	17.7	160.8	26.3	660
Switzerland	11.3	26.5	15.7	396
Turkey	4.7	13.0	7.7	388
Taiwan	8.6	9.2	7.7	308
Norway	10.3	37.2	18.6	474
Indonesia	1.3	2.6	2.7	81.5
South Africa	5.5	21.5	6.6	165

Figure 1 Environmental footprints of household consumption across countries. The figure includes the world average and 43 selected countries from EXIOBASE, ordered alphabetically by country codes. The world average includes all 43 countries and the five rest-of-the-world regions.

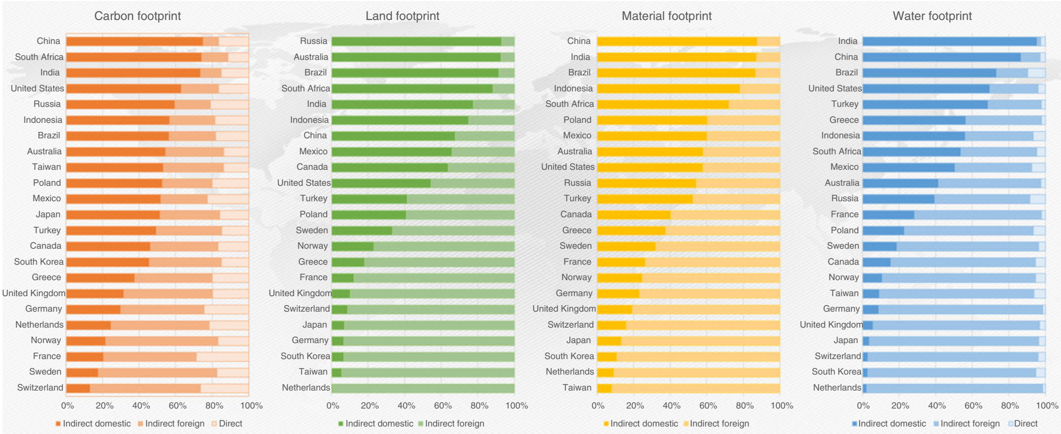

Figure 2 Indirect versus direct environmental impacts of household consumption across 23 selected countries. The figure separates household consumption footprint on direct (pressures that are emitted directly by consumption activities), indirect domestic (embodied in domestically produced products and services), and indirect foreign (embodied in imported products and services) across selected countries available in EXIOBASE. Households are not accountable for direct environmental impacts in relation to land and material use in EXIOBASE. Countries have been ordered by their share of indirect domestic impacts. Check the supporting information available on the Web for an overview of all 43 countries.

Luxembourg stands out with a low share of domestic indirect emissions, approximately 1.4 t CO_2-eq/cap in 2007 or 8% of the country's carbon footprint (figure 2). China, on the other hand, relies strongly on domestic production to satisfy local household demand, with indirect domestic impacts accounting for 92% of the country's total footprint.

Households emitted 4.4 Gt CO_2-eq directly through activities involving combustion of fuel amounting to roughly 20% of global GHG emissions from household activity. On average, direct carbon emissions originate from the use of transport (73%) and household fuel (27%). The share of direct GHG emissions is largest for households in France and Belgium, more than 28%. The larger fraction of carbon impacts occurs in the form of emissions embodied in purchases, as opposed to direct impacts. On a global scale, GHG emissions embodied in household purchases are driven by consumption of services (27%), shelter (25%), manufactured products (17%), mobility (15%), and food (13%).

Figure 3 presents an analysis of the carbon intensity of different consumption categories of EU households. Mobility has the highest amount of emissions per unit of household expenditure within the EU, 3.4 kg CO_2-eq/EUR (figure 3). Through driving own vehicles, EU households emit roughly half of the GHG emissions related to mobility directly, a total of 0.7 Gt CO_2-eq. The remaining mobility-related emissions are indirect emissions, in particular, consumption of gasoline and diesel (0.4 Gt CO_2-eq) and motor vehicles (0.2 Gt CO_2-eq). Shelter is similarly significant for the carbon footprint of EU households, comprising 26% of their impacts. This consumption category has a lower carbon intensity, 0.9 kg CO_2-eq/EUR, though it is associated with a higher share of household expenditure. Of of the six consumption categories, services are least carbon intensive; however, 45% of household expenditure is directed toward consumption of services, hence, the category's contribution of 17% from the total carbon impacts within EU.

Land Footprint

Almost 65 million square kilometers (km^2) of global land use was required to meet household demand in 2007. As a result, roughly 70% of the global land use was embodied in household purchases, with the ratio reaching up to 94% for Russia and South Africa. Other countries with developed resource-intensive forestry sectors, such as Canada and Finland, rely strongly on wood products for domestic construction and investments, hence, their lower relative importance of households (figure 2).

Together, the purchases of households in Russia, China, the United States, Brazil, and Australia account for more than 48% (31 million km^2) of total land resources embodied in household consumption in 2007. The EU contributed 15% (9.6 million km^2). GDP correlates weakly with household land requirements, with a correlation coefficient of 0.38. Australia has the most extensive per capita land footprint, 0.16 km^2/cap, more than 16 times higher than the global average of 0.01 km^2/cap. Russia has the second largest impact per capita at 0.07 km^2/cap. The two countries are also the ones with the highest share of household impacts embodied in domestic production, equivalent to more than 93% of land use. Australian land use is embodied in household purchases of food products, whereas shelter requirements dominate the land footprint of Russian households. Other forestry-rich countries, such as Norway and

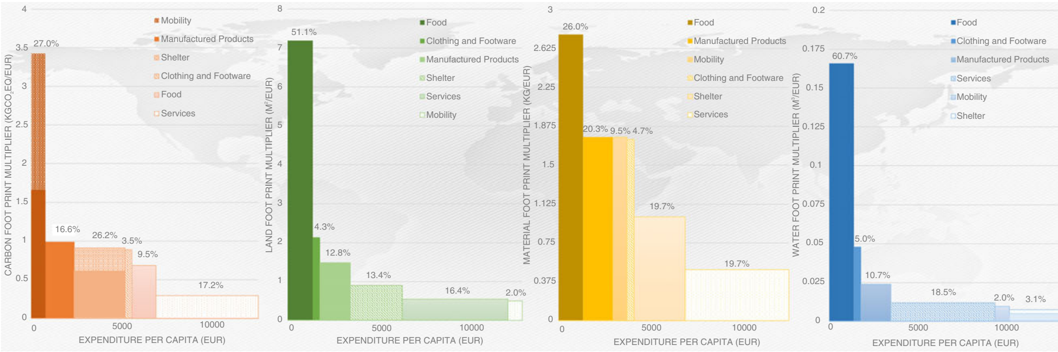

Figure 3 Contribution of consumption categories to the carbon, land, material, and water footprint of EU households. The contribution of consumption categories to the total environmental footprints can be split into two parts: the quantity of products within the category bought, measured by expenditure per capita in EUR, and the footprint intensities measured by footprint multipliers—the environmental impact per EUR of expenditure in the category. Consumption categories in the legend have been ordered by their environmental intensity (by magnitude of multipliers). The footprint multipliers are measured in kg CO_2-eq/EUR for carbon, m^2/EUR for land, kg/EUR for material, and m^3/EUR for water. The percentage labels describe the share of a category's footprint from the total footprint of household consumption within EU. The lighter shaded parts of "Shelter" and "Mobility" columns denote direct GHG emissions and water use by households. Check the supporting information on the Web for a breakdown of countries' footprint across consumption categories. EU = European Union; EUR = euro; kg CO_2-eq = kilograms carbon dioxide equivalent; m^2 = square meters; m^3 = cubic meters; GHG = greenhouse gas.

Finland, similarly have a significant portion of land use linked to purchases of wood and other forestry products.

Smaller EU economies face geographical restrictions and limited resources encouraging them to satisfy a larger share of household demand through imports from the developing world. As depicted in figure 2, households in Luxembourg, the Netherlands, and Belgium give rise to the highest land footprint per capita within the EU, although only a negligible fraction of that reflects domestic land use, between 1% and 3%. A significant share of the land impacts of the countries is owing to imports of crops and seeds from Brazil, China, and the United States. The Netherlands, for example, relies strongly on imported feed for its developed livestock industry (Tukker et al. 2014).

On a global scale, 46% of the land use occurs to meet household demand for food, followed by shelter and services, contributing 26% and 15%, respectively. Food has the largest land multiplier within the EU, with 7.2 square meters (m^2)/EUR spent on food. Household consumption of nonclassified food items entails a significant fraction of resource use across EU countries, around 2.6 km^2. Clothing is the second most land-intensive of consumption categories (figure 3), though it is associated with only 4% of the land use by EU households. Mobility is the least land-intensive consumption category requiring 0.5 m^2/EUR. Area covered by roads and other transportation infrastructure are not included in the estimate.

Material Footprint

The global material footprint of households amounted to 32 Gt in 2007, which is equivalent to 48% of the total raw materials that were extracted and used that year (table 1). Two fifths of the total material use fulfills consumption requirements of households in the United States, China, India, and Brazil. In 2007, households from the United States alone contributed to the largest material footprint in absolute values, 5.5 Gt or 17% of the global material impacts. More than one quarter of this amount was used to enable local consumption of products of meat cattle, processed food, and hotel and restaurant services. In comparison, the EU has a household material footprint of 7.1 Gt.

On a per capita basis, Luxembourg and Australia stand out with high levels of material footprint, 27.6 and 26.3 t/cap, respectively. Other developed economies show similar levels of household material impacts, hence, the correlation of 0.87 between national GDP and material footprint. In comparison, the global average amounts to 4.9 t/cap. Across the selected 43 countries, India has the lowest value of material impacts per capita, 2 t/cap.

Forty percent of global household material impacts (13 Gt) can be linked to internationally traded commodities across the 43 countries and five RoW regions. For Luxembourg, only 2% of the material footprint results from domestic extraction of materials, equivalent to a total of 0.2 million tonnes (Mt) in 2007. The rest of the material footprint, a total of 13 Mt, can be linked to household consumption of foreign products with highest environmental impacts embodied in imports of raw materials (e.g., crude oil, sand, and clay) from Russia and China and chemicals (e.g., fertilizers) from India.

In the case of Australia, 58% of households' total material footprint in 2007, around 322 Mt, is linked to extraction of raw materials from the domestic natural environment. The material footprint embodied in imports is dominated by industrial materials (e.g., sand and clay, and coal) from China. Norway has the third largest material footprint per capita. More than three fourths of the embodied material impacts relate to foreign extraction, especially imports from China and Russia. The country is a net exporter of materials such as stone and crude oil.

Globally, 36% of the material footprint arising from household activity can be attributed to food consumption, followed by services (23%) and manufactured products (17%). A comparison of the material intensities of consumption categories in the EU (figure 3) shows food to have the highest material multiplier, with 2.8 kilograms (kg) of extracted materials embodied per EUR. More than 11% of EU households' material footprint is embodied in consumption of processed food and dairy products (0.8 Gt). Consumption of manufactured products is the second largest contributor to the material footprint of EU households, with 20% (1.8 kg/EUR).

Water Footprint

In 2007, the global blue water footprint associated with household consumption is 1,386 cubic kilometers (km^3). Thus, households accounted for 81% of the total use of fresh water resources, followed by fixed capital formation (10%) and demand from governments (5%).

A total of 670 km^3 or 48% of global water impacts is embodied in household activity from India, the United States, and China. The per capita footprint is smallest in Indonesia, with 82 m^3/cap, and largest in Luxembourg, with 820 m^3/cap, with a global average of 210 m^3/cap. Again, the GDP level correlates positively with household freshwater use, with a coefficient of 0.74. Our choice of environmental indicator, however, could potentially influence the findings. Blue water consumption does not take into account the variation of crop water needs owing to the climate with dry warm climates, such as Spain, requiring much irrigation (Steen-Olsen et al. 2012).

On average, less than 5% of total household water footprint is in the form of direct consumption of water resources. Russia, Canada, the United States, and Norway stand out among the countries, with the largest per capita direct water use by households ranging between 28 and 25 m^3/cap. With regard to water use embodied in global supply chains, consumption of agriculture and livestock products required a total of 975 km^3 of water resources, or 74% of the indirect water footprint. The second largest contributor to blue water footprint is the services sector demanding approximately 18% of global household footprint. South Korea has the largest contribution of services to water use: 34% of the total footprint or 5.3 km^3. Hotel and restaurant services have the highest water intensity. Water footprint multipliers are ranked similar to the land footprint multipliers within the EU, with food being most intensive (0.17 m^3/EUR), followed by clothing (0.05 m^3/EUR) and manufactured products (0.02 m^3/EUR).

Approximately 27% of household water footprint was embodied in imports (370 km^3). Luxembourg has the highest fraction of impacts embodied in imports amounting to 99% with high importance of food imports, such as seeds, grains, vegetables, and fruits. Greece has the second highest per capita footprint, approximately 700 m^3, which is relatively equally distributed across domestic extraction (57%) and imports (41%) of indirect water resources, with the latter largely linked to food and agricultural products. Emerging economies such as the Brazil, Russia, India and China (BRIC) countries, are self-sustained when it comes to their water consumption.

The environmental impacts of household consumption are strongly correlated with consumer expenditure as listed in table 2. The expenditure elasticity of carbon is positive and significant at the 1% level, meaning that as household income levels rise, the carbon footprint increases by 66% for each doubling of household spending. The land and water footprint further have a positive statistical association with household expenditure, though differences in the expenditure variable explain a much lower fraction of the variation of the resource use across countries. Elasticity of food and shelter have the lowest R^2, likely reflecting the relevance of other determinants of land and water use such as natural resource availability and other geographical conditions (Hertwich and Peters 2009). A further breakdown of expenditure elasticities on a sectoral level shows that environmental impacts from staple food purchases (e.g., wheat, cereal grains, seeds, and nonclassified crops) do not increase significantly with household expenditure, unlike the footprint of dairy and meat products.

The share of emissions and resources use for production of nonprimary consumption items, such as some services, manufactured products, and clothing consumed by households, is much smaller in emerging economies and strongly driven by rising levels of disposable income and expenditure. This is reflected in the higher elasticities coefficients of those consumption categories across the footprint indicators (table 2).

Discussion and Conclusions

This study provides a comprehensive insight into the global environmental impacts by households. It highlights the significance of environmental pressure arising from households, with their consumption giving rise to more than 60% of global GHG emissions and between 50% and 80% of total resource use. A significant portion of the emissions and resource use are embodied in internationally traded commodities.

The regression analysis introduces household expenditure as a positive and highly significant determinant of household environmental impacts, with an elasticity coefficient varying between 0.40 for water and 0.66 for carbon. National income is also positively correlated with the footprints, which is consistent with our expectations that higher disposable income of households reflects more purchases of products, hence, higher levels of embodied impacts. The correlation coefficient describing the relationship between GDP and household land use is smaller than the coefficients regarding the other footprints, suggesting the importance of other factors for the variation of land use. For example, previous studies have investigated the

Table 2 Elasticity of footprints with respect to total household expenditure, by footprint and consumption category

	Carbon footprint		*Land footprint*		*Material footprint*		*Water footprint*	
	ε	R^2	ε	R^2	ε	R^2	ε	R^2
Total	0.66***	0.83	0.56***	0.49	0.54***	0.85	0.40***	0.54
Direct impact								
Shelter	0.70*	0.08	—	—	—	—	0.20*	0.07
Mobility	0.80***	0.83	—	—	—	—	—	—
Indirect impact								
Shelter	0.58***	0.44	0.45**	0.20	0.73***	0.54	0.75***	0.60
Food	0.41***	0.62	0.49***	0.41	0.29***	0.46	0.30***	0.35
Clothing	0.58***	0.63	0.76***	0.65	0.63***	0.62	0.67***	0.62
Mobility	0.77***	0.79	0.80***	0.68	0.76***	0.81	0.54***	0.38
Manufactured products	0.75***	0.86	0.88***	0.69	0.75***	0.87	0.72***	0.77
Services	0.75***	0.81	0.91***	0.69	0.71***	0.81	0.69***	0.51

Note: Expenditure elasticity of consumption measures the effect of changes in per capita expenditure on the environmental footprints. The "Total" row shows the estimated coefficients when using the total per capita footprints as dependent variables that are regressed on household expenditure per capita. To compare coefficients across consumption categories, additional regressions are run separately where dependent variables are the environmental footprints of the different categories. The land and material footprints are associated with no direct impacts by households. The symbols *, **, and *** denote significance levels, α, of 10%, 5%, and 1%, respectively.

influence of resource availability on the national land-use footprints (Wiedmann et al. 2015; Weinzettel et al. 2013). We also find the largest consumers of land, Russia (forest land) and Australia (arable and pasture land), to have the highest share of domestic land impacts, suggesting that households tend to consume more resources when they are readily available. It should be noted that our land indicator currently does not capture any potential differences in the land's fertility across countries; how the choice of indicator affects results should be investigated further.

We confirm earlier conclusions about mobility, shelter, and food being the most important consumption categories (Hertwich and Peters 2009). Though their environmental relevance varies across footprint indicators, the three categories consistently make up between 55% and 65% of the total impacts. Food has the highest land, material, and water multipliers, hence, switching a EUR of expenditure from food to clothing in the EU, for example, results in a reduction of 5.1 m^2 of land resources, 1.0 kg of extracted materials and 0.1 m^3 of fresh water. At the same time, any redirecting expenditure from the food category to any other services would cause increases in GHG emissions. This brings attention to an important implication for any policy targeting reductions of household footprints in absolute terms, particularly, what is the environmental opportunity cost of reducing impacts in a certain category. Conversely, a redirection of household expenditure toward less resource-intensive services is more straightforward given that it results in impact reduction across all footprint indicators. Nevertheless, one should always regard a certain degree of nonsubstitutability of consumption items and categories in the redesign of household expenditure patterns.

Further, GHG emissions and resource use from food consumption rise with income, though at a lower rate than non-primary consumption categories. The result is mainly driven by rising importance of dairy and meat products, processed food, and tobacco products at high household expenditure. The large footprints of nonclassified food items necessitate further investigation.

Mobility has the largest carbon footprint in the EU, with household impact roughly evenly distributed between direct tailpipe emissions from driving private cars and emissions embodied in purchases of fuel, transport services, and vehicles. The magnitude of direct emissions is also strongly determined by total household expenditure, with a doubling of the total expenditures resulting in an 80% rise of direct transport emissions. The results draw attention to potential limitations of policy measures to reduce GHG emissions related to transportation. For starters, if the sole effect of rising purchasing power on mobility demand was to switch to more fuel-efficient vehicles, we would have found a negative coefficient on direct emissions. Instead, our results can be explained by other effects taking place as well. For instance, low-income households are generally characterized by lower car ownership rates; hence, they are more likely to resort to low-carbon alternatives, such as public transportation and cycling (Steen-Olsen et al. 2016). Further, the more efficient use of own vehicles potentially gives rise to rebound effects that could be direct (driving more owing to increased affordability of fuel) and indirect (switching purchasing power to other goods). Nevertheless, we show that mobility has the largest carbon multiplier in the EU context, according to which a redirection of 1 euro of household expenditure to the second most carbon-intensive category, manufactured products, would result in a carbon cut of 2.4 kg CO_2-eq. This is rather encouraging for residential GHG mitigation programs, especially in areas with high motor vehicle emissions.

In 2007, shelter, more particularly, the consumption of electricity, wood products, housing fuel, and real estate services, contributed to 26% of the carbon, 13% of the land, and 20% of the material footprints within the EU, with average impact intensity relative to other consumption categories. Statistical analyses indicate insignificant elasticity coefficients on direct shelter impacts and significant, though smaller, coefficients on indirect ones. As a basic need, shelter is relatively more important at low income; in contrast, we expect the importance of nonprimary categories to increase at a higher rate with rising consumer purchasing power.

Our model assigns environmental impacts according to household expenditure on products and services; hence, the model potentially leaves out relevant consumption financed by the government and investment. The implications are twofold. First, potential differences might occur across countries in terms of which goods and services households cover directly, thus, imposing limitations to the comparative analysis. For example, the sector of health and social work services has the second largest carbon footprint out of all industrial sectors in the United States, whereas its lower relative importance in other countries relates to health-related expenditures often being covered by governments or employers (Hertwich 2011; Ferguson and MacLean 2011; Weber and Matthews 2008). Second, the model falls short when it comes to endogenizing capital, such as residential buildings and road infrastructure used by household and underestimates household impacts related to shelter and mobility. Actual and imputed rent is included in the calculation of environmental impacts from real estate services, which contributed to 4% of global carbon and material footprints by households in 2007.

A significant fraction of household footprints in the developed world depends on impacts embodied in imports from poorer countries. This limits developed countries' ability to decouple impacts from wealth (and expenditure) through technology and efficiency improvements. Our study further has some limitations regarding the macro-level expenditure elasticities. The cross-country regression results need to be interpreted cautiously in the absence of corresponding expenditure elasticities at the micro level (Baiocchi et al. 2010; Hubacek et al. 2014). For example, we have no way of observing potential changes in the expenditure-footprint relationship across countries and socioeconomic groups. Further, previous studies have signaled for the benefits of spatial aggregation in relation to the calculation of environmental impacts embodied in trade (Su and Ang 2010).

Our study provides a comprehensive insight about the environmental consequences of household purchasing decisions and informs mitigation strategies about the consumption categories with the highest environmental relevance. This work goes beyond presenting a snapshot of household emissions and resource use and provides a different perspective on footprint determinants and strategies for environmentally driven reallocation of household spending. Ultimately, a behavioral change may have a significant potential to balance economic growth with environmental performance.

Acknowledgments

This work is part of the GLAMURS project financed by the European Union's seventh framework program (contract 613420). EXIOBASE 2.2 was constructed in the CREEA project, financed by the same program (contract 265134).

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

Supporting Information S1: This supporting information provides information about household environmental footprints including total and per capita absolute values across countries and RoW regions and consumption categories; information about total household expenditure, population, and national GDP (purchasing power parity; PPP); version of figure 2 depicting all 43 countries; and further description of the database.

Article 2

Mapping the carbon footprint of EU regions

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Supplementary materials can be found online at:

http://iopscience.iop.org/article/10.1088/1748-9326/aa6da9/meta

Volume 12, 054013, Pages 1546-1555, DOI: 10.1088/1748-9326/aa6da9

Environmental Research Letters

CrossMark

OPEN ACCESS

RECEIVED
19 July 2016

REVISED
5 April 2017

ACCEPTED FOR PUBLICATION
18 April 2017

PUBLISHED
12 May 2017

LETTER

Mapping the carbon footprint of EU regions

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Keywords: household consumption, regional assessment, carbon footprint, consumer expenditure surveys, environmentally extended multiregional input-output analysis, greenhouse gas emissions, climate policy

Supplementary material for this article is available online

Abstract

While the EU Commission has encouraged Member States to combine national and international climate change mitigation measures with subnational environmental policies, there has been little harmonized effort towards the quantification of embodied greenhouse gas (GHG) emissions from household consumption across European regions. This study develops an inventory of carbon footprints associated with household consumption for 177 regions in 27 EU countries, thus, making a key contribution for the incorporation of consumption-based accounting into local decision-making. Footprint calculations are based on consumer expenditure surveys and environmental and trade detail from the EXIOBASE 2.3 multiregional input-output database describing the world economy in 2007 at the detail of 43 countries, 5 rest-of-the-world regions and 200 product sectors. Our analysis highlights the spatial heterogeneity of embodied GHG emissions within multiregional countries with subnational ranges varying widely between 0.6 and 6.5 tCO_2e/cap. The significant differences in regional contribution in terms of total and per capita emissions suggest notable differences with regards to climate change responsibility. The study further provides a breakdown of regional emissions by consumption categories (e.g. housing, mobility, food). In addition, our region-level study evaluates driving forces of carbon footprints through a set of socio-economic, geographic and technical factors. Income is singled out as the most important driver for a region's carbon footprint, although its explanatory power varies significantly across consumption domains. Additional factors that stand out as important on the regional level include household size, urban-rural typology, level of education, expenditure patterns, temperature, resource availability and carbon intensity of the electricity mix. The lack of cross-national region-level studies has so far prevented analysts from drawing broader policy conclusions that hold beyond national and regional borders.

1. Introduction

Under the Europe 2020 growth strategy, EU has committed to cutting its territorial greenhouse gas (GHG) emissions to 20% below 1990 levels as a part of the Climate and Energy package (European Commission 2016). Core policies such as the EU Emissions Trading System (EU ETS) and the Effort Sharing Decision set binding targets for each Member State covering the major polluting sectors (Eurostat 2016). The Commission has also recommended that environmental issues be tackled on subnational level (European Commission 2011a, 2011b). The research community has pointed out to the importance of regional and local policy for environmental impact mitigation (Meng *et al* 2013, Harris *et al* 2012, Wood and Garnett 2010, 2009). Cross-country analyses conceal wide spatial heterogeneity within countries, which may potentially obstruct the effect of impact mitigation policies (Godar *et al* 2015, Chancel and Piketty 2015).

Regions systematically focus on mitigation of impacts occurring on their territory (Somanathan *et al* 2015, Andonova and Mitchell 2010), e.g. by deciding on waste treatment options or transport planning. While such actions may reduce emissions locally, production activity may simply move somewhere else (Girod *et al* 2014, Skelton 2013). Studies have signalled for the empirical significance of carbon off-shoring (Harris *et al* 2012, Aichele and Felbermayr 2012), e.g. showing that countries committed to the Kyoto Protocol have about 8% more carbon-intensive imports than uncommitted ones (Aichele and Felbermayr 2015). Products may accumulate a significant load of environmental impacts along global supply chains before they reach final consumers and such effects are unaccounted for from a purely territorial perspective. Just as a city draws most of its agricultural goods from hinterland, a region may have a far greater impact in reducing emissions from the goods they consume than the goods they produce (Lenzen *et al* 2008). The consumption-based accounting establishes a link between local consumption and its global environmental consequences (Wood and Dey 2009).

Consumption-based policies may be effective to sustain regional competitiveness and limit the opportunity for carbon leakage (Girod *et al* 2014). Despite this potential, policy makers have generally failed to adopt consumption-based measures on the subnational level (Turner *et al* 2011). This is at least partly due to the lack of harmonized and actionable impact information on that level of regional detail. To our knowledge, no subnational assessment of household carbon footprints has been made available for the whole European Union. Previous studies on regional footprints cover only a limited number of (generally non-EU) countries or consumption sectors (Curry and Maguire 2011, Minx *et al* 2013, Minx *et al* 2009, Jones and Kammen 2014, Deng *et al* 2015, Zhang and Anadon 2014, Zhou and Imura 2011, Adom *et al* 2012, Miehe *et al* 2016, Larsen and Hertwich 2011, Lenzen *et al* 2004). This has prevented analysts from having a broader policy vision that goes beyond national and regional borders.

In this study, we assess household carbon footprints across 177 regions in EU27 providing a higher spatial detail than prior cross-country assessments (Tukker *et al* 2016, Ivanova *et al* 2015, Hertwich and Peters 2009). Furthermore, while there has been a significant amount of work on determinants of household energy use and GHG emissions (e.g. Lenzen *et al* 2006, Weber and Matthews 2008, Baiocchi *et al* 2010), conclusions have generally been drawn from individual-level assessments under a narrow spatial scope. Prior findings inform about the relevance of *socio-economic effects* such as income, household size, education, social status and degree of urbanization (Jones and Kammen 2014, 2011, Baiocchi *et al* 2010, Minx *et al* 2013, Lin *et al* 2013, Wilson *et al* 2013b), *geographic effects* such as temperature and geographic location (Tukker *et al* 2010, Newton and Meyer 2012) and *technical effects* such as the infrastructural context (Chancel and Piketty 2015, Tukker *et al* 2010, Sanne 2002). We would like to test whether influences that have been previously identified as important for consumption impacts may be apparent on the regional aggregated level as well (see table 1).

2. Data and methods

We conduct an environmentally extended multiregional input-output (MRIO) analysis combining the use of regionally disaggregated demand from consumer expenditure surveys (CESs) and product carbon intensities from the EXIOBASE 2.3 database. A detailed description of the data and methodology as well as the complete regional footprint inventory is provided in the supplementary information (SI) available at stacks.iop.org/ERL/12/054013/mmedia.

The majority of CESs adopt a common consumption nomenclature, i.e. the Classification of Individual Consumption by Purpose (COICOP) (European Communities 2003). The spatial coverage is based on the Nomenclature of territorial units for statistics (NUTS) regions, a hierarchical regional classification within EU (Eurostat 2017). Footprint accounts at NUTS 2 level allow for distinguishing between basic regions for the application of regional policies. Table 2 identifies differences in terms of collection year, product detail and spatial coverage.

EXIOBASE 2.3 provides national carbon intensities across 200 product sectors and detailed bilaterally by places of origin (i.e. global supply-chain information across 43 countries and 5 rest-of-the-world regions). The database facilitates environmental analysis by incorporating increased detail of environmentally important processes (Wood *et al* 2014, Stadler *et al* 2014). A detailed overview of EXIOBASE is provided by Wood *et al* (2015) and in the SI. We estimate indirect emissions embodied in the supply chains of purchases and the direct emissions occurring when households burn fuel (e.g. when driving). All emissions are reported in CO_2-equivalent (CO_2e) per year using GWP100 (Solomon *et al* 2007).

2.1. Regional footprint calculations based on CES-MRIO methodology

Several reconciliation steps were necessary for the CES-MRIO matching (Steen-Olsen *et al* 2016). The harmonization of product classification between the surveys (e.g. COICOP) and EXIOBASE was achieved using country-specific CES-MRIO concordance matrices. We matched classifications conceptually and through consulting EXIOBASE's household demand accounts as a benchmark. EXIOBASE's household accounts include all household consumption except the one registered as governmental spending or investment, e.g. health and social work

Table 1. Summary of exploratory hypotheses on relevant factors for consumption-based GHG emissions per capita. The table broadly agrees with an assessment conducted by Hertwich (2005) on energy consumption and CO_2 emissions.

	Factors	Direction of effect	Reasoning	Sources
Socio-economic	Income (INC)	+	Income directly determines household capacity to consume. The direction of the effect is more difficult to predict on product level, e.g. there exist inferior goods whose consumption goes down as income rises	Wilson *et al* 2013b, Tukker *et al* 2010, Peters and Hertwich 2008, Jackson and Papathanasopoulou (2008), Lenzen *et al* (2006)
	Household size (HHSIZE)	—	Household members share electrical appliances and require less individual living space Economies of scale in different consumption domains	Tukker *et al* (2010), Lenzen *et al* (2006), Wilson *et al* (2013b), Minx *et al* (2013)
	Urban-rural typology (URBAN)	+/−	Urban typology is associated with more compact development and larger availability of public transport, but studies have also found urban inhabitants to have higher impacts associated with food, leisure travel and manufactured products	Marcotullio *et al* (2014), Tukker *et al* (2010), Lenzen *et al* (2006), Minx *et al* (2013), Wiedenhofer *et al* (2013)
	Tertiary education (EDUC)	+/−	Education and social status redesign individual preferences towards more or less emission-intensive lifestyles	Chancel and Piketty (2015)
	Basic need spending (BASIC)	—	Spending on necessities (food, shelter, clothing) may be associated with lower emissions per unit of expenditure compared to that of transport and manufactured products	Ivanova *et al* (2015), Steen-Olsen *et al* (2016)
	Dwelling size (NROOMS)	+	Housing size determines the requirements of space heating/cooling and building material use	Lenzen *et al* (2006), Newton and Meyer (2012)
Geographic	Temperature (HDD)	+/−	Lower average temperatures (north) and low-quality, poorly isolated homes (south) are associated with higher emissions. Rising temperatures may also drive energy use for cooling.	Minx *et al* (2013), Wiedenhofer *et al* (2013), Chancel and Piketty (2015)
	Landscape (FORESTAREA)	+/−	Access to forest and semi-natural area may foster low-carbon leisure activities, but also encourage the consumption of available resources	Ivanova *et al* (2015)
Technical	Electricity mix intensity (EMIX)	+	The local electricity mix directly determines the carbon intensity of products produced and consumed locally (e.g. housing emissions)	Tukker *et al* (2010)

services, road infrastructure (Ivanova *et al* 2015). Tourism and transport sectors are potentially more affected by residents' spending abroad, which may bring about higher uncertainty of results in those sectors (Usubiaga and Acosta-Fernández 2015). See the SI, appendix 2 and 3, for details on the data and method.

The phenomenon of under-reporting in CESs has been well-documented in prior literature (Steen-Olsen *et al* 2016). Households systematically under-report small and irregular purchases, e.g. private goods (clothing), alcohol and tobacco, and certain luxuries (alcohol and food away from home) (Bee *et al* 2015). Methodological differences in the survey design may also give rise to under-reporting relative to the national accounts, e.g. the UK and Czech Republic differ in excluding owner-occupied imputed rent from their surveys (Eurostat 2015b). An additional vector was added to the CES-MRIO concordance matrix allocating expenditure missing in the surveys to the particular under-reported products.

Further harmonization of consumer demand in terms of year coverage, currency and valuation scheme was necessary. Consumer Price Indices by consumption item and country enabled a conversion to 2007 constant prices (Eurostat 2015a). Expenditure recorded in the surveys is reported in purchaser prices (PPs) or the price final consumers pay in the store, while carbon intensities in EXIOBASE are set for demand in basic prices (BPs). EXIOBASE provides transport, trade and tax layers enabling the conversion from PPs to BPs, reallocating the trade and transport costs of products to the respective services.

2.2. Explaining spatial variation of regional carbon footprints

This study employs a regression model to explore the relationships between household emissions and socio-economic, geographic and technical factors on the regional level. Multiple empirical studies and theoretical considerations (see table 1) informed the choice of model specification subject to data availability

Table 2. CES information by country. Sweden and the Netherlands have been excluded due to lack of regional detail. Only NUTS 1 data available for France, Germany and the UK (larger regions than NUTS 2). For more information about the accuracy, timeliness and comparability of the surveys refer to the EU quality report (Eurostat 2015b).

EU Countries	Year	Product detail	Spatial detail	N	Source
Austria	2010	COICOP 2	NUTS 2	9	Household Budget Survey, Statistik Austria
Belgium	2010	COICOP 3	NUTS 2	3	Household Budget Survey, Statistics Belgium
Bulgaria	2010	COICOP 3	NUTS 2	6	Household Budget Survey, NSI
Cyprus	2007	200 products	NUTS 2	1	EXIOBASE 2.3
Czech Republic	2011	COICOP 3	NUTS 2	8	Household Budget Survey, Czech Statistical Office
Denmark	2010	COICOP 3	NUTS 2	5	Household Budget Survey, Statistics Denmark
Estonia	2007	200 products	NUTS 2	1	EXIOBASE 2.3
Finland	2012	COICOP 3	NUTS 2	5	Household consumption expenditure, Statistics Finland
France	2011	COICOP 3	NUTS 1	9	Household Budget Survey, Insee
Germany	2010	28 products	NUTS 1	16	New consumption module, German Socio-Economic Panel
Greece	2014	COICOP 3	NUTS 2	13	Family Budget, EL.STAT
Hungary	2006	COICOP 3	NUTS 2	7	Household Budget Survey, KSH
Ireland	2010	COICOP 3	NUTS 2	2	Household Budget Survey, Central Statistics Office
Italy	2010	COICOP 1	NUTS 2	21	Household Budget Survey, Istat
Latvia	2007	200 products	NUTS 2	1	EXIOBASE 2.3
Lithuania	2007	200 products	NUTS 2	1	EXIOBASE 2.3
Luxembourg	2007	200 products	NUTS 2	1	EXIOBASE 2.3
Malta	2007	200 products	NUTS 2	1	EXIOBASE 2.3
Poland	2010	COICOP 1	NUTS 2	16	Household Budget Survey, Central Statistical Office
Portugal	2010	COICOP 3	NUTS 2	7	Household Budget Survey, Statistics Portugal
Romania	2012	COICOP 1	NUTS 2	8	Family Budgets Survey, NIS
Slovakia	2013	COICOP 1	NUTS 2	4	Household Budget Survey, Slovak Statistics
Slovenia	2007	200 products	NUTS 1	1	EXIOBASE 2.3
Spain	2010	COICOP 1	NUTS 2	19	Household Budget Survey, INE
United Kingdom	2010	COICOP 4	NUTS 1	12	Living Costs and Food Survey, ONS

constraint at the regional aggregation level. We conduct relative weights analysis to better understand the importance of each predictor while addressing the potential for multicollinearity. We employ cluster-robust errors to account for the potential correlation between regional observations belonging to the same country due to sharing of national features, e.g. national legislation, institutions, social and cultural norms, common infrastructure standards etc. Cluster-robust standard errors have been widely used as a method to tackle interclass correlation (Cameron and Miller 2015, Cameron and Trivedi 2009). The clustered regression approach produces unbiased clustered standard errors provided that there are a sufficient number of clusters (Petersen 2009). See the SI, appendix 1 and 4, for more detailed description of the variables in the model, statistical procedure and sensitivity analysis.

3. Results

3.1. Household carbon footprint at subnational level

Figures 1(*a*) and (*b*) map total and per capita household carbon footprint across EU regions. Descriptive footprint statistics and complete dataset can be found in the SI. North Rhine-Westphalia and Bavaria in Germany together emit about 410 $MtCO_2e$ or 40% of German emissions. Other regions with significant footprints include regions from the UK (e.g. South East, London), Germany (e.g. Baden-Württemberg, Lower Saxony), Italy (e.g. Lombardy) and France (e.g. Parisian Region). Regional footprints are normally distributed with mean and median of 11 tCO_2e/cap and standard deviation of 3 tCO_2e/cap. The top emission decile (i.e. 10% of the population with highest emissions per capita) includes regions with average carbon footprint between 22 and 16 tCO_2e/cap. The top decile emits 15% of the total EU emissions equivalent to 815 $MtCO_2e$. In comparison, the bottom decile (i.e. 10% of the population with lowest emissions per capita) make up about 5% of EU emissions with contribution of 5–7 tCO_2e/cap. The carbon intensity distribution across EU regions is skewed to the right with a mean, median and standard deviation of 1.1, 0.9 and 0.4 $kgCO_2e$/EUR BPs, respectively. The distributions of household carbon footprints and intensities can be found in SI figure 1.

Countries display different degrees of subnational heterogeneity. Italy, Spain, Greece and the UK stand out with the highest footprint ranges. The range refers to the interval between the lowest and highest regional estimates within a specific multi regional country (including outside values). Italy has a range from 6.9 to 13.4 tCO_2e/cap, equivalent to 94% of the footprint of the lowest-impact region, Sicily. Other countries such as Slovakia and Portugal display lower absolute ranges, although still substantial when compared to the magnitude of regional footprints, leading to high dispersion indices of 0.23 and 0.17 respectively. Denmark and Czech Republic show the most uniform distribution of carbon footprints across their regions.

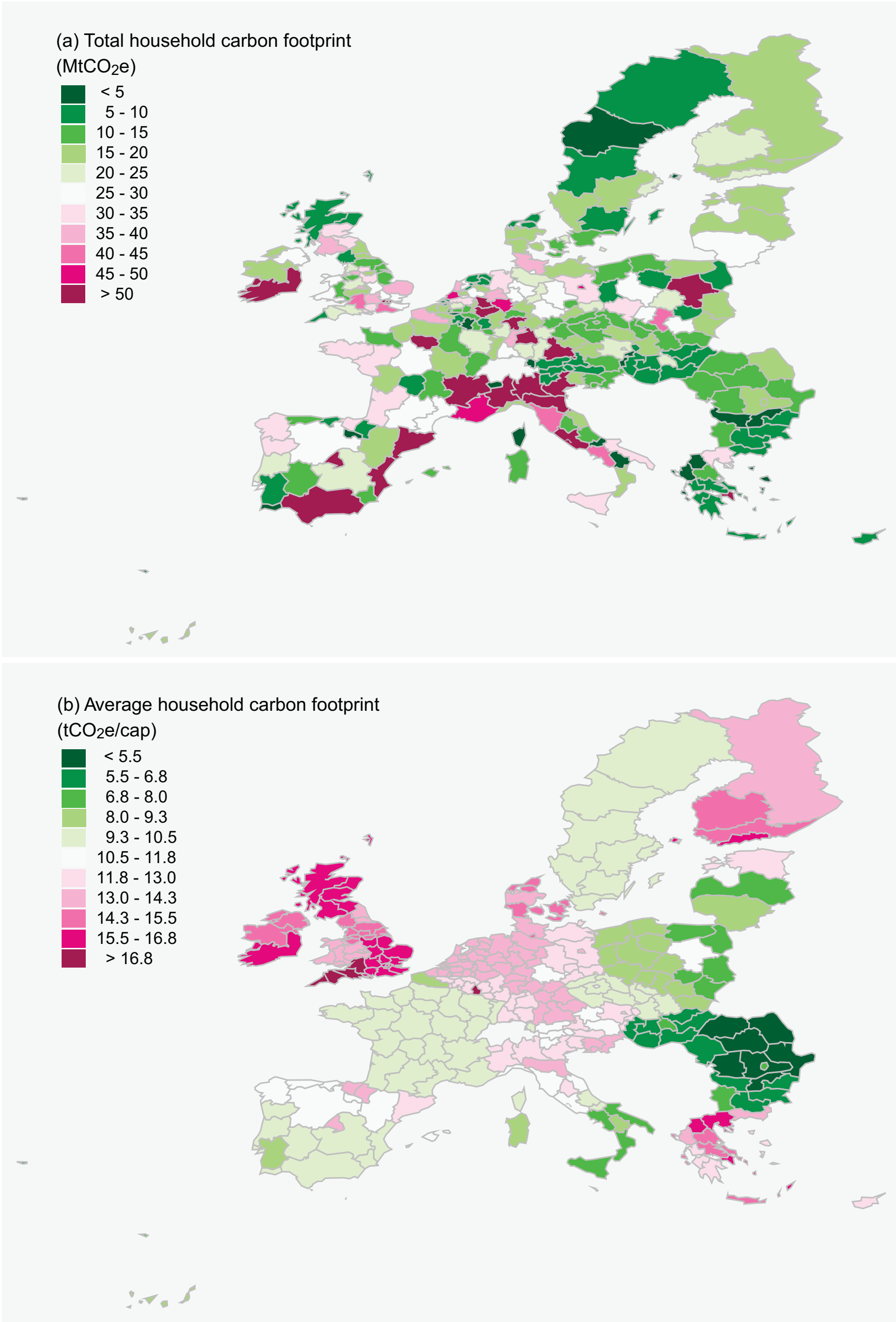

Figure 1. (*a*) Total household carbon footprint across NUTS 2 regions in $MtCO_2e$ (calculated using regional population size from Eurostat) and (*b*) per capita household carbon footprint across NUTS 2 regions in tCO_2e/cap. National averages of consumption used for Sweden and the Netherlands, see table 2 for the level of regional detail for the rest. See SI figure 2 for direct-indirect emission division and appendix 6 for the complete regional dataset. For an interactive version of the per capita map see http://www.environmentalfootprints.org/regional

Table showing within-country absolute and relative dispersion for the regional totals and by consumption domain has been included in SI table 2–3 (SI, appendix 1).

Direct household emissions comprise about 20% of EU's household carbon footprint with a ratio varying between 9%–27% across regions. The majority of direct emissions are tailpipe emissions

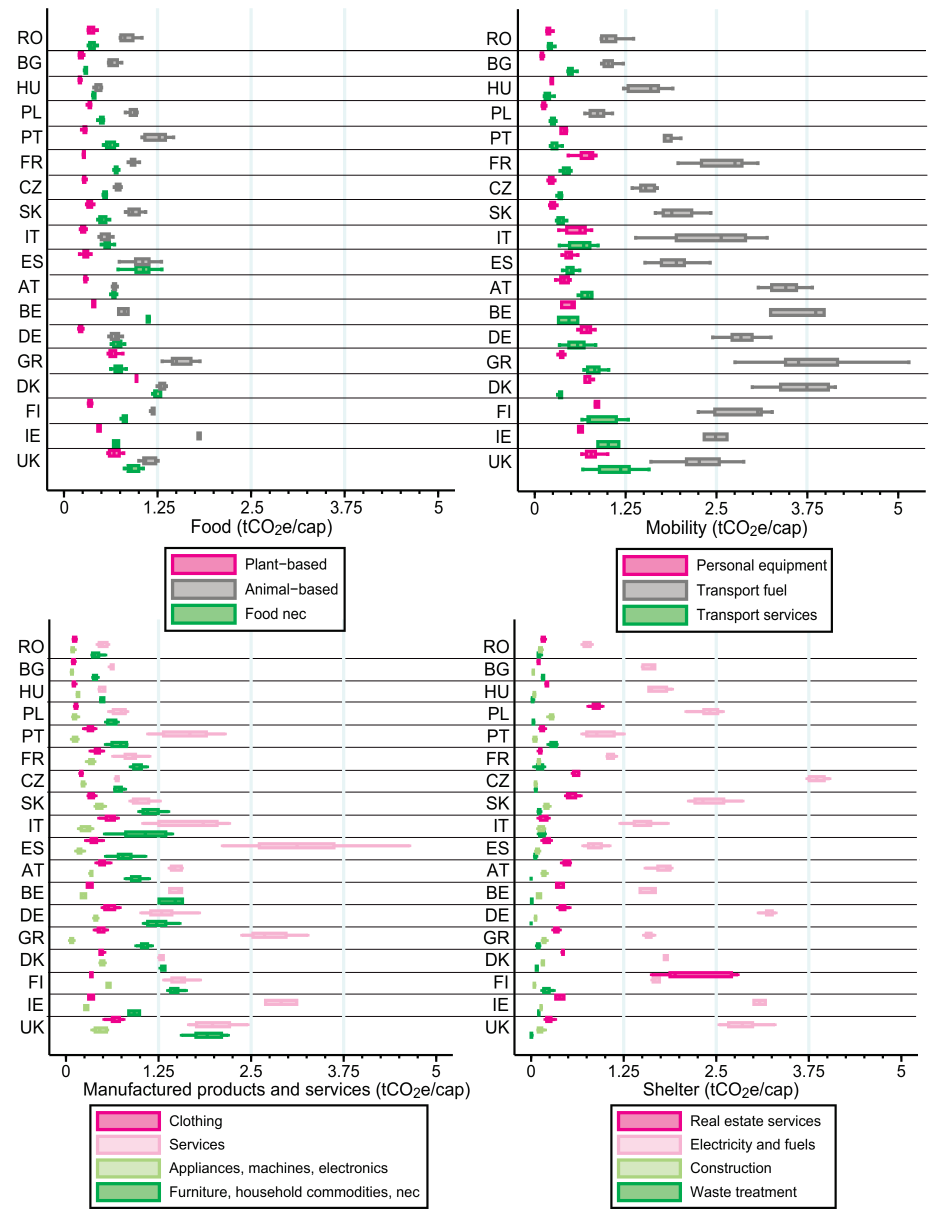

Figure 2. Subnational distribution of the household carbon footprint by consumption category measured in tCO_2e/cap. The graph excludes all one-region countries and outside values (more than 1.5 × IQR below or beyond). The boxes describe 25th percentile (left hinge), median and 75th percentile (right hinge). The adjacent lines describe the min and max (in the absence of outside values). Countries are ordered by median household carbon footprint. See table 2 for number of regions across countries, SI tables 2–3 for domain-specific descriptive statistics of within-country absolute and relative dispersion and appendix 5 for product overview across consumption categories developed in consideration of ISIC detailed structure (United Nations 2017) and household consumption patterns.

associated with private use of vehicles. Transport contributes to about 30% of EU household emissions with importance across regions varying between 13%–44% with the majority of impacts coming from burning of transport fuel (see figure 2). Luxembourg has the highest mobility emissions in Europe with 9.6 tCO_2e/cap where emissions from transport fuel amount to 83% (direct and indirect). Prior analysis has discussed the potential bias associated with the so-called tank tourism effect (occurring when residents of neighbouring countries fill up their tanks in countries with lower fuel prices); particularly, Luxembourg stands out with the biggest transport emission variation between the residence and territory principle due to price differences in gasoline and diesel with neighbouring countries, pointing to higher uncertainty of results (Usubiaga and Acosta-Fernández 2015, Statistisches Bundesamt 2010). Transport fuel emissions are also particularly significant in France due to commuting to adjacent countries, as well as Greece and Cyprus, which have large vessel fleets in proportion to their size resulting in a higher fuel use of marine bunkers (Usubiaga and Acosta-Fernández 2015). The contribution of indirect emissions from private vehicles, other transport equipment and public transport services is generally much lower.

Food is a significant source of household emissions contributing to about 17% of EU household emissions and a varying importance of 11%–32% across regions. The capital region of Denmark stands out with the highest food-related emissions with 3.9 tCO_2e/cap or about 27% of the total regional footprint. These findings are in agreement with prior analysis of the Danish consumption-based emissions embodied in food (Edjabou and Smed 2013). The largest absolute inter-regional differences in terms of food emissions occur in Spain and Greece, where the intervals between the lowest and highest regional estimates amount to 1.3 and 0.9 tCO_2e/cap respectively. This variation is mostly associated with within-country differences in the consumption of animal products and processed food. Animal-based products are associated with higher magnitude and dispersion of impacts across regions relative to plant-based products and non-classified food items. The analysis reveals significant inter-regional differences in diet composition. For example, animal-based products contribute to only 33%–38% of food emissions across regions in Belgium and Denmark, while in Slovenia such products bring about 79% of food emissions. Slovenia also stands out with highest animal-based emissions per capita in absolute terms, particularly 2.9 tCO_2e/cap.

There are significant differences in the way emissions from clothing and other manufactured goods are distributed across countries and regions. Compared to other consumption categories, clothing contributes to a relatively low share of total household emissions, only 4% of EU household emissions. Regions from the UK have some of the highest emissions associated with clothing in Europe, particularly, London and Northern Ireland with 0.8 tCO_2e/cap. The relative importance of clothing is highest in Italy with 5%–7% of carbon impact of consumption. The UK and Italy demonstrate the highest footprint range with 0.3 tCO_2e/cap. Similar in magnitude and dispersion is the category of appliances, machinery and electronics, contributing to 1%–4% of regional impacts. About 10% of all household emissions in the EU are associated with other manufactured products, particularly, furniture, household commodities and other non-classified items. Emissions from services are associated with about 14% of the EU's household carbon footprint with varying significance across regions, between 7%–41%. Spain stands out with higher relative importance of services for the household carbon footprint, largely associated with hotel and restaurant services. Similar to transport, estimates may be biased from improper assignment of tourist expenditure in EXIOBASE. The services footprint is highest in the Balearic Islands region with 4.6 tCO_2e/cap, or 41% of the regional emissions.

About 22% of the carbon footprint of EU households is associated with housing. Direct shelter emissions comprise about 28% of shelter footprint, e.g. due to combustion of fuel for heating at home. The shelter footprint per capita ranges between 1 tCO_2e/cap (the Canary Islands) and 5.5 tCO_2e/cap (Åland in Finland) with a rather right-skewed distribution. Finland stands out with the largest range of shelter footprint of 1.9 tCO_2e/cap. Finnish regions are classified by the lowest household sizes in our sample at 1.5 persons per household. In a study of Finnish households, Heinonen and Junnila (2014) have confirmed the significance of the economies of scale effect on energy consumption rates, especially regarding housing-related emissions. Furthermore, there are vast differences in terms of the real estate service footprint, between 5%–58%, suggesting differences in the way housing impacts (e.g. from construction) are classified across countries. The Prague region stands out with a particularly high shelter footprint from fuel and electricity, 4 tCO_2e/cap. Housing fuel and electricity impacts are rather significant in the whole of Czech Republic (36%–39% of household footprint), also characterized by some of the highest heating degree days and carbon intensity of the electricity mix (EEA 2011).

As a validity check, regional footprint results have been scaled up to the national level and compared to estimates developed using EXIOBASE's household demand. Deviations of CES results are within a ten-percent range from EXIOBASE's estimates for all countries in the sample (see SI, appendix 7). Exceptions are Slovakia and Greece, where the regional analysis produces footprint results that are 17% and 15% lower than EXIOBASE totals respectively (mostly due to underestimation of animal-based food and services emissions). It should be noted that better consumption detail in terms of COICOP resolution may be associated with more constrained CES-MRIO bridge and therefore potentially higher deviation from EXIOBASE's estimates.

3.2. Determinants of the household carbon footprint

Table 3 presents the regression output and table 4 supplements it with the raw relative weights and their significance across model specifications. The point of this analysis is not to establish causal inference relationships; the aim is to attempt to explain the observed regional variation in household carbon footprints using available NUTS 2 level data for factors hypothesized to influence carbon footprints and which have been considered in the literature. Significance

Table 3. Regional determinants of household carbon footprint measured in $kgCO_2e$/cap based on 177 EU regions. Dependent variables from left to right: household carbon footprint of all categories and by food, clothing, mobility, services, manufactured products, shelter. Cluster-robust standard errors in parenthesis. Significance level: $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$. Income (in thousand EUR/cap) and income square term (INC2), household size, predominantly urban (based on population density), tertiary education (in % of the population aged 30–34 with tertiary education), basic need expenditure (in % of total expenditure), number of rooms, monthly heating degree days (measuring the severity of the cold on an average month with 15 °C as a heating threshold for outdoor temperature), forest and semi-natural area (in thousand m^2/cap), electricity mix intensity (categorical variable with the lowest value of 1 for electricity intensity between 0 and 0.20 $kgCO_2e$/kWh and value of 6 for electricity intensity between 1.0 and 1.2 $kgCO_2e$/kWh). SI table 1 includes a detailed list of sources for all independent variables, while regression results based on other model specifications and more disaggregated consumption categories are explored in SI tables 6–7. Full regional dataset is included in appendix 6.

Household carbon footprint ($kgCO_2e$/cap)	(1) All	(2) Food	(3) Clothing	(4) Mobility	(5) Services	(6) Manufactured products	(7) Shelter
INC	644.059***	7.378	51.643***	264.515***	96.533***	67.497**	156.936*
	(177.49)	(57.29)	(6.23)	(80.90)	(32.85)	(29.24)	(76.25)
INC2	−12.016**	0.020	−0.928***	−3.736	−1.865	−0.824	−4.685**
	(4.79)	(1.73)	(0.18)	(2.20)	(1.13)	(0.90)	(2.22)
HHSIZE	−1276.909	77.490	−58.816	−762.377	508.252*	−295.539	−755.106**
	(1160.14)	(250.42)	(63.11)	(473.35)	(291.52)	(217.01)	(365.84)
URBAN	−722.863	−104.976	−8.889	−646.939**	−17.306	50.807	5.741
	(545.42)	(140.14)	(24.27)	(240.58)	(154.98)	(69.40)	(111.67)
EDUC	62.580**	27.704***	−1.482	11.923	19.215*	1.481	3.739
	(27.34)	(6.48)	(1.36)	(11.98)	(9.82)	(5.82)	(9.03)
BASIC	−75.931*	−21.921***	−0.237	−20.685	−12.606	−13.338	−6.882
	(39.23)	(7.62)	(3.08)	(14.44)	(8.14)	(10.41)	(11.52)
NROOMS	−1117.122	−16.347	−93.316*	−1026.314	332.596	−78.308	−248.821
	(1667.34)	(410.90)	(47.42)	(798.23)	(464.77)	(219.07)	(455.33)
HDD	−0.774	−1.467	−0.400	−3.065	−5.846***	1.394*	8.558***
	(5.79)	(1.28)	(0.24)	(2.82)	(1.14)	(0.81)	(1.23)
FORESTAREA	28.994	9.515	−0.213	15.629	32.642***	−4.159	−24.303**
	(32.79)	(8.76)	(1.65)	(15.30)	(9.56)	(5.56)	(9.60)
EMIX	847.177**	90.228	26.957	77.978	121.967	49.678	481.578***
	(391.68)	(77.00)	(16.36)	(143.15)	(100.27)	(69.46)	(119.69)
Constant	9674.502	2050.048	253.203	5202.427**	−284.983	1556.325	922.721
	(6456.60)	(1434.61)	(290.20)	(2483.13)	(1754.96)	(961.31)	(1556.35)
R^2	0.72	0.51	0.74	0.67	0.69	0.69	0.72
Adjusted R^2	0.70	0.48	0.73	0.65	0.67	0.67	0.71
N observations	173	173	173	173	173	173	173
N clusters	25	25	25	25	25	25	25

Table 4. Model summary displaying the raw relative weights of different independent variables across model specifications. The relative weights sum to the R^2 presented in table 3. The significance tests are based on confidence intervals performed with an alpha value of 0.05 and 10 000 number of iterations for the bootstrapping procedure. Significance level: $^{**}p < 0.05$.

Predictors	(1) All	(2) Food	(3) Clothing	(4) Mobility	(5) Services	(6) Manufactured products	(7) Shelter
INC and INC2	0.29**	0.03	0.45**	0.35**	0.09**	0.30**	0.04**
HHSIZE	0.08**	0.00	0.09**	0.09**	0.03**	0.11**	0.08**
URBAN	0.01	0.01	0.01	0.02	0.01	0.02	0.00
EDUC	0.08**	0.22**	0.01	0.02	0.08**	0.03**	0.01
BASIC	0.12**	0.17**	0.03	0.06**	0.09**	0.09**	0.01
NROOMS	0.09**	0.04	0.10**	0.07**	0.08**	0.08**	0.01
HDD	0.00	0.02	0.04**	0.02	0.26**	0.04**	0.32**
FORESTAREA	0.01	0.01	0.00	0.02	0.04**	0.00	0.02
EMIX	0.04**	0.01	0.02	0.01	0.01**	0.01**	0.23**

level and explanatory power of the factors vary widely across models.

3.2.1. Socio-economic factors

Income has the highest explanatory power in our model explaining 29% of the regional household carbon footprint (table 4). The negative and significant quadratic term suggests that the trend is levelling off. Thus, a thousand-EUR rise in income would result in roughly 450, 300 and 150 $kgCO_2e$/cap increase in footprint at the 25th, 50th and 75th income percentile of the regional sample respectively (at income levels of

8100 EUR/cap, 14 100 EUR/cap and 20 800 EUR/cap respectively). The income-footprint curve reaches its peak at an annual net income of around 26 800 EUR/cap and starts to decline (within the income range of our regional sample). The concave nature of the relationship is strongly driven by the domains of clothing and construction with turning points of 27 800 EUR/cap and 26 600 EUR/cap respectively. There is a strong linear effect of income for the domains of services and manufactured products, where a thousand EUR-increase in annual income is associated with about 100 and 70 $kgCO_2e$/cap emission rise. The consumption categories of clothing, mobility and manufactured products appear particularly income-elastic with the income effect explaining 45%, 35% and 30% of the regional emission variance respectively. Clothing registers the highest income elasticity of 0.86.

Increasing the average household size of a region by one person leads to a drop in the average person's emissions associated with electricity and housing fuels (750 $kgCO_2e$/cap, significant at 5%) and waste treatment (80 $kgCO_2e$/cap, significant at 5%). Household size explains 8% of the regional shelter footprint variance. The urban-rural typology is insignificant in most of the models except for mobility. Predominantly urban regions have on average 650 $kgCO_2e$/cap lower emissions from land transport and, therefore, lower direct and indirect emissions from transport fuels. Both variables of household size and urban-rural typology vary little across regions, which may affect the significance of their effects.

A one-percent point increase in the regional population with tertiary education is associated with an increase of about 60 $kgCO_2e$/cap in household emissions, mainly driven by food consumption. While the significance of the effect is consistent across all food sub-categories, the magnitude of the coefficient is largest for animal-based products according to which a one-percent point increase in tertiary education is associated with a 17 $kgCO_2e$/cap rise in animal-based food footprint. Education explains about 22% of the variability in regional food emissions, which makes it the most important factor for that domain in our model. The basic need ratio ranks second in terms of importance for food-related emissions, where one-percent point increase in the regional household budget on basics brings about a decrease in food-related emissions of about 20 $kgCO_2e$/cap. The regression analysis across more disaggregated consumption categories suggests that there are significant economies of scale driven by dwelling size. An increase of average dwelling size by one room brings about a decrease about 130 $kgCO_2e$/cap in both construction and waste treatment.

3.2.2. Geographic and technical factors

Heating degree days have a positive and highly significant impact on the regional shelter emissions explaining more than 30% of the variation in the depending variable. A one-degree increase in the severity of the cold on an average month is associated with an emission increase of approximately 7 $kgCO_2e$/cap from housing fuel and electricity use for heating and 2 $kgCO_2e$/cap from both real estate services and construction. The need for heating is likely lessened by the more stricter building standards enforced in northern European countries where households consume less energy for heating per unit floor area and heating degree day (Balaras *et al* 2007). Moderately increased emissions from heating in colder regions are offset by lower emissions embodied in services, particularly hotel and restaurant services. A rise in the forest area of a region by a thousand square meters per capita is associated with a 40 $kgCO_2e$/cap drop in electricity and housing fuel emissions. Households have been noted to consume more resources when they are readily available (Ivanova *et al* 2015) suggesting that availability of forest products may encourage the use of wood for heating, which is assumed to be carbon neutral in EXIOBASE.

The electricity mix intensity explains an additional 23% of the variance in shelter emissions. An increase in the electricity mix intensity by 0.2 $kgCO_2e$/kWh results in a rise of housing impacts of 480 $kgCO_2e$/cap. The majority of this effect (about 80%) can be explained by changes in the regional footprint associated with electricity and housing fuels, though significant effect is noted for the energy-intensive sub-categories of real estate services and construction as well. This factor captures the carbon intensity of the domestic electricity mix and, therefore, its effect would be proportionate to the share of domestically produced consumption.

4. Discussion

This is the first study to quantify region-level consumption-based GHG emissions associated with household consumption in a comprehensive framework across the European Union. It combines the use of regionalized consumer expenditure data with multiregional input-output framework to trace carbon impacts along global supply chains and highlights the most carbon-contributing consumption activities across regions. The regression analysis allows to test potential effects identified from other groupings of the CES data on the regional aggregate level. Prior studies have emphasized the need for a broader international comparative perspective in the examination of social driving forces of emissions (Rosa and Dietz 2012).

Socio-economic factors such as income, household size, education, dwelling size and basic consumption generally explain between 15%–69% of the subnational heterogeneity (11%–44% excluding income) in emissions with their statistical significance varying widely across regression models. Countries with higher inter-regional income inequality (e.g. Italy, the UK and Spain) also stand out with wider emission ranges consistent across consumption domains, particularly income-elastic domains such as clothing, services and manufactured products. These results are in line with previous findings suggesting that macro-trends in GHG emissions are heavily driven by socio-economic factors, while geographic and infrastructural effects have limited effect on the regional level of analysis (Minx *et al* 2013, Baiocchi *et al* 2010). Income has a varying significance across consumption domains. Prior studies have suggested that rising affluence may shift the composition of consumption (not only the scale) and, thus, it may or may not compensate for the tendency that increased affluence comes at increased GHG emissions (Rosa and Dietz 2012). In an EU27 country panel, Sommer and Kratena (2016) also find a relative decoupling effect due to a higher saving rate and less emission intensive consumption of top income quintiles, which however does not compensate for the much higher levels of consumption. We find a stronger evidence for levelling off of the emission-income curve rather than turning points (i.e. the so-called environmental Kuznets curve hypothesis) with only a small fraction of the regional sample lying beyond the suggested threshold of 26 800 EUR annual individual income (< 3%). It has been suggested that thresholds instead signal for critical points differentiating between different income groups of countries (Liao and Cao 2013).

Shelter and mobility demonstrate rather high regional dependence with an emission share ranging between 10%–46% and 13%–44% respectively. Impacts from housing and transport dominate countries such as Austria, Denmark and France (with regional mobility footprints between 2.8–5.2 tCO_2e/cap), Finland, Poland and Czech Republic (with regional shelter footprint between 3.0–5.5 tCO_2e/cap), Bulgaria and Hungary (both shelter and mobility). Prior literature has suggested that increases in household size reduce emissions per capita and increase eco-efficiency, most pronounced in the housing domain (Tukker *et al* 2010, Weber and Matthews 2008, Wilson and Boehland 2005). This is in agreement with our results as we find a negative and highly significant effect of household size particularly in the domain of shelter. Our regional analysis does not confirm prior hypotheses that urban residents and smaller dwelling sizes contribute to lower housing impacts due to the dwelling structure (Tukker *et al* 2010, Lenzen *et al* 2006). Nevertheless, the insignificance of the variables may be a result of the large and mixed (in terms of urban-rural typology) regions and housing price differences between densely and sparsely populated areas. Additional factors with potential importance include characteristics of the dwelling stock (e.g. type, age and level of refurbishment), residential floor area, types of construction materials and fuels used and proportion of combined heat and power generation among others (Wilson *et al* 2013a, Tukker *et al* 2010). Selected geographic and technical factors explain up to 34% and 23% respectively of the regional shelter-related emissions, thus, outweighing the importance of socio-economic controls for the shelter domain. It has been previously suggested that geographic and infrastructural effects may be more significant at a finer spatial detail (Minx *et al* 2013).

Income is the single most important determinant of transport emissions explaining 35% of their variation, where a rise in individual annual income of a thousand EUR increases emissions by about 265 $kgCO_2e$. Predominantly urban households contribute to about 650 $kgCO_2e$/cap less on average compared to their rural counterparts on the regional level of data aggregation. Prior studies have signalled that denser urban forms are associated with lower GHG emissions from road passenger transport, but potentially higher contribution from air travel and other passenger transportation (Jones and Kammen 2015, Ottelin *et al* 2014, Ornetzeder *et al* 2008). A systematic bias may arise if air travel is under-reported in consumer expenditure surveys as an infrequent purchase (Bee *et al* 2015). Additional private and institutional indicators expected to affect regional transport-related emissions include private vehicle ownership and technical characteristics of the vehicle fleet, density of road network, public transport availability and proximity to an airport (Waisman *et al* 2013, Tukker *et al* 2010). The exclusion of such factors from the model may give rise to omitted variable bias.

Food emissions are rather income inelastic. They vary between 1.0 and 3.9 tCO_2e/cap across regions with an impact share of 11%–32%. Similar spatial invariability of environmental food-related impacts has been shown for the neighbourhood level in Canada and the USA (Wilson *et al* 2013a, Jones and Kammen 2015). Basic consumption share is associated with lower food emissions when controlling for income. This effect may occur due to a shift of spending from food to shelter in order to offset rising utilities expenditures for low-income households (Schanzenbach *et al* 2016, Bhattacharya *et al* 2003) and carbon intensity differences between basic and discretionary spending (Ivanova *et al* 2015). A one-percent point rise in the population with tertiary education brings about an increase in the regional food footprint of close to 30 $kgCO_2e$/cap, where education explains about 22% of the variation in regional food-embodied emissions. Duarte *et al* (2012) also found better educated households to contribute to higher consumption and GHG emissions than less educated ones, although at a lower emission intensity of consumption. Our results confirm the generally uncertain direction of the education effect previously outlined by Chancel and Piketty (2015).

We have already discussed the potential for omitted variable bias due to limited availability of data on NUTS level. Such omitted factors include institutions (e.g. demographic institutions of governance leading to greater environmental protection), social psychology and culture (e.g. values, beliefs, norms and world-views) (Rosa and Dietz 2012).

There are certain limitations to our method with regards to footprint calculations. CESs provide no physical layer of consumption or price information, so we apply average product intensities. This may cause a systematic bias in our analysis as luxurious consumption has potentially lower resource intensity per unit expenditure than mass-produced products of the same category (Hertwich 2005). Sectors classified by a larger gap between residence and territory estimates such as tourism and transport sectors are likely associated with higher uncertainty of results. Whilst a systematic assessment of uncertainty is not feasible here (CES data had no uncertainty estimates associated with it), national level studies point to uncertainty ranges of about 5%–10% for carbon footprints (Lenzen *et al* 2010, Karstensen *et al* 2015, Moran and Wood 2014), with relatively higher uncertainty for smaller economies, or in the context of this study, regional populations. With regards to the statistical analysis, our dataset is relatively non-uniform across countries with varying number of regions, survey collection years and consumption detail. The size of the regions may be too large to allow for significant variation of socio-economic, geographic and technical factors. Prior research has also signalled for the *modifiable areal unit problem* according to which spatial aggregation of grouping of data comes at the price of inevitable loss of information or bias (Wong 2009).

Our study provides comprehensive insights into the subnational spatial variation of household carbon footprints and allows regions to monitor consumption-based emissions and consider them when setting priorities for climate policies. Ultimately, regions differ in their emissions and reduction potential, which also implies differences in their climate responsibility for national mitigation strategies.

Acknowledgments

This work is an output of the GLAMURS project financed by the European Union's seventh framework program (contract 613420). The EXIOBASE database was constructed in the CREEA project, financed by the same program (contract 265134). The authors thank Radek Lonka for technical and graphics assistance and Nancy Lea Eik-Nes for writing assistance and language editing. Data collection for the study was enabled by national statistical offices; special thanks to Irina Macsinga, Statistics Greece and the German Socio-Economic Panel for data acquisition in the cases when region-level consumption information was less accessible.

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Article 3

Carbon mitigation in domains of high consumer lock-in

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See A-3.2 for Supplementary Information

Volume 52, Pages 117-130, DOI: 10.1016/j.gloenvcha.2018.06.006

Global Environmental Change 52 (2018) 117–130

Contents lists available at ScienceDirect

Global Environmental Change

journal homepage: www.elsevier.com/locate/gloenvcha

Carbon mitigation in domains of high consumer lock-in

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ARTICLE INFO

Keywords:
Climate change mitigation
Lock-In
Consumer behavior
Carbon intensity
Determinants
Policy measures

ABSTRACT

As climate policy needs to address all feasible ways to reduce carbon emissions, there is an increasing focus on demand-side solutions. Studies of household carbon footprints have allocated emissions during production to the consumption of the produced goods, and provided an understanding of what products and consumer actions cause significant emissions. Social scientists have investigated how attitudes, social norms, and structural factors shape salient behavior. Yet, there is often a disconnect as emission reductions through individual actions in the important domains of housing and mobility are challenging to attain due to lock-ins and structural constraints. Furthermore, most behavioral research focuses on actions that are easy to trace but of limited consequence as a share of total emissions. Here we study specific alternative consumption patterns seeking both to understand the behavioral and structural factors that determine those patterns and to quantify their effect on carbon footprints. We do so utilizing a survey on consumer behavioral, attitudinal, contextual and socio-demographic factors in four different regions in the EU. Some differences occur in terms of the driving forces behind behaviors and their carbon intensities. Based on observed differences in mobility carbon footprints across households, we find that the key determining element to reduced emissions is settlement density, while car ownership, rising income and long distances are associated with higher mobility footprints. For housing, our results indicate that changes in dwelling standards and larger household sizes may reduce energy needs and the reliance on fossil fuels. However, there remains a strong need for incentives to reduce the carbon intensity of heating and air travel. We discuss combined effects and the role of policy in overcoming structural barriers in domains where consumers as individuals have limited agency.

1. Introduction

Scientists and policy makers are increasingly calling for demand-side solutions for mitigating climate change (Creutzig et al., 2018; Wood et al., 2017). Shelter, transport, food, and manufactured products have been identified as high-impact consumption domains (Hertwich and Peters, 2009; Ivanova et al., 2016) and mitigation actions and targets have been suggested (Girod et al., 2014). However, targeting consumer behavior poses its own challenges (Barr et al., 2011; Dietz et al., 2009; Klöckner, 2015). Behavioral scientists have questioned the presumption of control consumers have over their consumption in the context of systematic barriers (Akenji, 2014; Sanne, 2002). Environmental footprints depend to a significant degree on external factors such as infrastructure and technology, institutions (e.g. social conventions, power structures, laws and regulations), and unsustainable habits, creating lock-ins (Jackson and Papathanasopoulou, 2008; Liu et al., 2015; Sanne, 2002; Seto et al., 2016). Such lock-ins reinforce existing social structures and may hinder a transition towards more sustainable systems (Geels, 2011), although opportunities for positive lock-ins have also been explored (Ürge-Vorsatz et al., 2018).

Here we explore the carbon footprints of mobility and housing, and the factors that may explain their variation. Mobility and shelter stand out among the highest contributors to the household carbon footprint (CF) in the EU (Ivanova et al., 2017, 2016), making their de-carbonization a high priority. While previous work has addressed some of these concerns in parts, this study integrates the investigation of attitudinal, structural and socio-economic factors of consumption choices and their CF in four EU regions, thereby enhancing policy relevance of the

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https://doi.org/10.1016/j.gloenvcha.2018.06.006
Received 6 February 2018; Received in revised form 11 May 2018; Accepted 13 June 2018
0959-3780/

results.

The importance of context for behavior has been a longstanding theme in consumer behavior research, where studies have broadly explained behavior through individual and contextual factors (Ertz et al., 2016; Newton and Meyer, 2012; Stern, 2000). According to the low-cost hypothesis, attitudinal variables have less influence when a behavior is too difficult to perform (e.g. due to high structural barriers). Mobility and energy behaviors are identified as typical high-cost domains (Diekmann and Preisendörfer, 2003; Klöckner, 2015) as complex decisions, such as location of residence and vehicle ownership, define the use-patterns for a long time (Klöckner, 2015).

Most research effort on sustainable consumption focuses on either the physical dimension (technology, supply chains, urban form) or the social dimension (attitudes, behavior) (Banister, 2008; Thomsen et al., 2014). For example, studies on behavioral drivers generally do not introduce footprint controls and instead rely on measuring pro-environmental behavioral proxies. This may introduce a behavior-impact gap (Csutora, 2012) and lead to targeting the most visible, or easy, rather than the most environmentally relevant behaviors (Klöckner, 2015). In contrast, studies that focus only on the technical characteristics leave out important factors for consumption change, such as attitudes, habits, and behavioral plasticity (Dietz et al., 2009; Thøgersen, 2013). The importance of socio-economic effects such as expenditure and income (Ivanova et al., 2017; Minx et al., 2013; Wilson et al., 2013a), household size (Ala-Mantila et al., 2014; Minx et al., 2013; Wilson et al., 2013b), urban-rural typology (Ala-Mantila et al., 2014; Heinonen et al., 2013; Minx et al., 2013), demographics (Baiocchi et al., 2010) and car ownership (Minx et al., 2013; Ornetzeder et al., 2008) for the household CF has been widely discussed (see Supplementary Information (SI) table 15). However, prior work differs in fundamental ways in terms of unit of analysis (Ivanova et al., 2017, 2016), consumption detail (Newton and Meyer, 2012), and geographical coverage (Heinonen et al., 2013; Minx et al., 2013).

Here we examine individual-level behavior and carbon intensity determinants separately, which is not a common practice; we do so to uncover potential differences in their driving forces. Determinants may also be significantly interrelated, e.g. with urban cores exhibiting different incomes and household types (Ottelin et al., 2015). Therefore, we explore combined effects and their footprint implications. Furthermore, we evaluate potential emission trade-offs from other consumption areas. Focusing on a single consumption domain may overlook substantial rebound effects, e.g. where lowering of emissions in one domain causes emission increases in another (Hertwich, 2005; Ornetzeder et al., 2008; Wiedenhofer et al., 2013). For an adequate mitigation of greenhouse gas (GHG) emissions from the consumption side, we argue that several main facets need to be considered:

- lifecycle emissions from various consumption domains
- technical and social dimensions of mitigation potential
- lock-in effects

Our study is the first one, to our knowledge, to combine these considerations in an analysis of carbon emissions that integrates consumption-based accounting with determinants studies in a policy-relevant framework.

2. Data and method

We examined consumption patterns through a survey on behavioral, attitudinal, contextual and socio-demographic factors in a survey sample of four European regions: Galicia (Spain), Lazio (Italy), Banat-Timis (Romania) and Saxony-Anhalt (Germany). The total sample included 1617 respondents, of which 1399 (85%) and 1407 (87%) provided enough detail for mobility and shelter-specific calculations, respectively. Details about survey design, sampling and distribution can be found in the SI "Survey design".

Below we present the CF calculator used as an input to our statistical analysis. The design of the calculator was informed by prior product-level input-output assessments of household consumption (Ivanova et al., 2017, 2016) and mixed approaches to cover emissions and behavioral aspects (Birnik, 2013; West et al., 2016). We focus on the domains of mobility and shelter, with an additional estimation of food and clothing consumption, to capture most of the GHG emissions of European households. For survey background information, uncertainty and validation on footprint calculations, see the SI "Carbon footprint calculations".

2.1. Mobility footprint calculations

We collected data on transport means and distance of regular return trips, including active transport (walk, bicycle, e-bicycle), private motorized transport (car, motorbike) and public transport (bus, tram, underground, train). Regular travel distance (bottom-up) was validated with the annual top-down estimate that car users provided. Additional adjustments were made in the cases of carpooling. We assumed regular travel of 35 weeks/year for work purposes and 40 weeks/year for private purposes. Observations with annual land travel above 80000 km/year (or 220 km/day) were treated as outliers, conforming to the upper limit of the top-down car-travel range. Air travel was based on annual number of short- and long-haul return flights with assumed distance of 2300 and 8000 km/return trip, respectively. See SI "Carbon footprint calculations" for a detailed discussion of the distance assumptions. We treated observations with a number of return flights above 365 in a year as outliers.

The total carbon intensity of mobility results from dividing the mobility footprint by the total distance travelled. Lifecycle (indirect) emissions from cradle-to-gate and direct tailpipe emissions were based on lifecycle assessment (LCA) studies and the Ecoinvent database (GWP100 in $kgCO_2eq$/passenger km (pkm)) (Frischknecht et al., 2005). The emission intensity of electricity mix was considered where relevant (GWP100 in $kgCO_2eq$/kWh, Ecoinvent). We utilized car- and fuel-specific intensities where additional car and fuel data were available. We allocated emission factors for air depending on flight length (see Ross, 2009). Fig. 1 visualizes our sample's mobility CF as a function of distance travelled (x-axis) and carbon intensity (y-axis).

The mean and median of annual land-based travel was about 9500 km (26 km/day) and 4900 km (13 km/day), respectively (Table 1). About 13% of the land-based distance was travelled actively, with an average daily return trip of 6 km (for sub-sample estimates see SI Fig. 1). Our sample had active travel with annual emissions of 4 $kgCO_2eq$/cap. About 29% of distance on land was travelled by public transport, with an average trip of 19 km/return trip. Private motorized travel was 5500 km/cap on average (or 22 km/daily return trip), with a footprint of 1.2 tCO_2eq/cap. About 36% of respondents owned a car and used it alone, while 51% shared the car with other members of the household.

With about 47% of respondents travelling to short-haul destinations, air travel was the largest contributor to mobility emissions (Fig. 1). Air transport brought about an annual CF of 2.4 tCO_2eq/cap on average, compared to 1.5 tCO_2eq/cap for land-based travel (Table 1). These estimates seem higher than prior MRIO assessments, which may be due to the lack of consistency in reporting standards for air transport calculation (Usubiaga and Acosta-Fernández, 2015).

2.2. Shelter footprint calculations

Energy use covers use of electricity (ELEC), space heating (SH) and water heating (WH). Annual electricity consumption was derived from reported monthly payments in winter and summer, discounting any space and water heating powered by electricity to avoid double-counting. Physical energy demand for space and water heating was modelled using the TABULA methodology based on Europe-

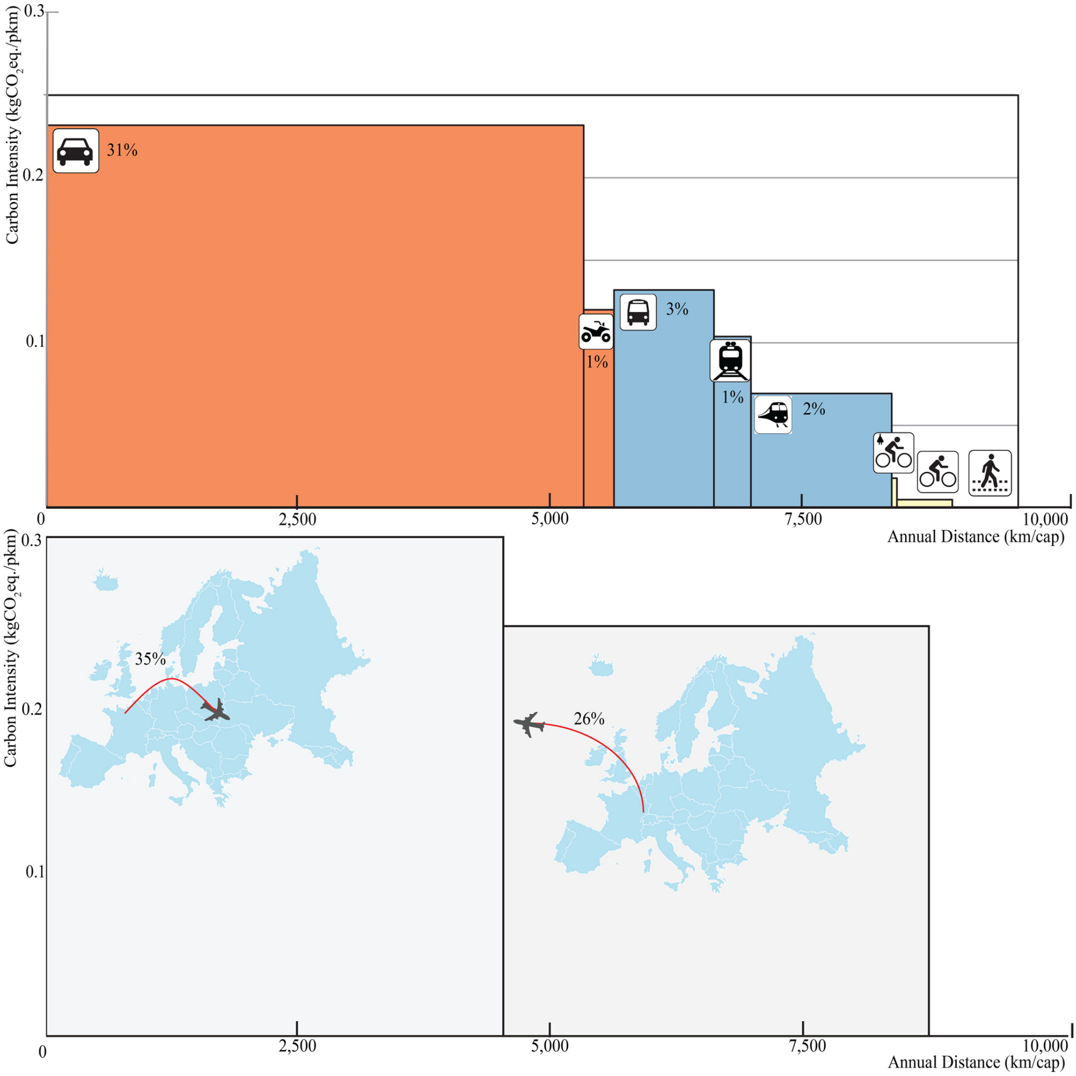

Fig. 1. Land and air mobility carbon footprint (CF) by travel mode showing carbon intensities (in $kgCO_2eq/pkm$) and distance (in km). The area of each rectangular depicts the CF of that transport mode and the %s - the footprint share from total mobility (all summing to 100%). The top graph displays land-based travel by car and motorbike (private motorized transport), bus, tram/underground and train (public transport), electric bike, bike and walking (active transport) (from left to right); the bottom graph displays air-based travel by short- and long-haul flights (from left to right).

representative dwelling sample (IWU, 2013). Regression coefficients were estimated for the effects of dwelling type, period of construction, refurbishment level and climate zone on typical energy demand per square meter ($R^2 = 0.48$). The total theoretical energy demand per square meter was then scaled up by living space and divided by the number of inhabitants in the household. Thus, our analysis excludes emissions embodied in construction materials, which have been quantified to vary widely, e.g. with shares between 2–38% for conventional buildings (Sartori and Hestnes, 2007). Embodied emission in construction materials gain more relevance for low-energy buildings, where they can account for up to 50% of total emissions (Blengini and Di Carlo, 2010; Dahlstrøm et al., 2012; Sartori and Hestnes, 2007). We also excluded private and communal energy costs embodied in housing management fees (Heinonen and Junnila, 2014). A prior assessment of communal electricity (studying housing companies) quantified it at about 5% of energy use and CO_2 emissions from energy consumption in multi-family apartment buildings (Kyrö et al., 2011). The carbon intensity of space and water heating was calculated based on the lifecycle emissions by heating source (in $kgCO_2eq/kWh$, Ecoinvent). We adopted region-specific carbon intensities of the electricity mix.

Fig. 2 depicts the shelter CF as a function of the carbon intensity of energy and energy use. Our sample had a mean annual energy use of 6200 kW h (17 kW h/day) and a median of 4700 kW h (13 kW h/day). Electricity comprised about 25% of average energy use and 42% of the shelter-related CF. Region-specific electricity mix had carbon intensity between 0.52 and 0.75 $kgCO_2eq/kWh$. About 47% of the shelter CF and 63% of energy use was associated with space heating. The mean and median of daily energy use for space heating was estimated to be 11 and

Table 1
Descriptive statistics. Means and standard deviations (in parenthesis) reported for the total sample and across the regional sub-samples. Descriptive statistics are reported for individuals as units of analysis (see SI "Descriptive Statistics").

		Definition and Unit	Total		Galicia (ES)		Banat-Timis (RO)		Lazio (IT)		Saxony-Anhalt (DE)	
Sample size		*No. respondents*	*1617*		*488*		*292*		*458*		*379*	
Land mobility footprint	LMOB_FP	Annual carbon footprint from land travel, tCO_2eq/cap	1.5	(2.2)	1.4	(1.9)	1.1	(2.0)	1.5	(2.1)	2.0	(2.5)
Air mobility footprint	AMOB_FP	Annual carbon footprint from air travel, tCO_2eq/cap	2.4	(6.8)	2.3	(4.5)	2.6	(7.7)	2.6	(5.9)	2.0	(9.0)
Electricity footprint	ELEC_FP	Annual carbon footprint from electricity use at home, tCO_2eq/cap	1.0	(1.4)	0.9	(0.9)	0.3	(0.5)	1.5	(2.2)	1.0	(0.9)
Space heating footprint	SH_FP	Annual carbon footprint from space heating, tCO_2eq/cap	1.1	(1.9)	0.8	(0.9)	1.0	(1.6)	0.7	(0.9)	1.9	(3.2)
Water heating footprint	WH_FP	Annual carbon footprint from water heating, tCO_2eq/cap	0.2	(0.1)	0.2	(0.1)	0.2	(0.1)	0.2	(0.1)	0.3	(0.1)
Land mobility distance	LMOB_DIS	Daily distance travelled by land, km/day	26.0	(34.7)	24.5	(34.3)	20.6	(33.7)	25.8	(30.6)	32.4	(39.7)
Short flights	AMOB_SHORT	Annual N short flights	1.96	(7.0)	2.27	(3.7)	1.98	(9.4)	2.11	(3.6)	1.30	(10.5)
Long flights	AMOB_LONG	Annual N long flights	0.51	(2.0)	0.39	(1.6)	0.58	(1.7)	0.57	(2.2)	0.54	(2.4)
One-user car	CAR_ONE	Share of respondents who own a car and use it alone	0.36	(0.48)	0.28	(0.45)	0.29	(0.45)	0.43	(0.50)	0.45	(0.50)
Many-user car	CAR_MANY	Share of respondents who own a car and share it with other household members	0.51	(0.50)	0.59	(0.49)	0.46	(0.50)	0.48	(0.50)	0.46	(0.50)
Attitude mob initiative	MINI_ATT	Attitude towards ride/car sharing initiatives/platforms, 7-point scale: 1. Very negative, 7. Very positive	5.2	(1.7)	5.6	(1.5)	4.4	(1.9)	5.3	(1.7)	5.3	(1.6)
Use mob initiative	MINI_USE	Use of ride/car sharing initiatives/platforms, 7-point scale: 1. Very negative, 7. Very positive	2.3	(1.9)	2.4	(2.0)	2.7	(2.0)	2.3	(1.8)	2.2	(1.7)
Electricity use	ELEC	Daily electricity use, kWh/day	4.3	(6.0)	4.7	(4.6)	1.2	(2.0)	6.2	(9.1)	4.2	(3.6)
Space heating use	SH	Daily space heating energy use, kWh/day	10.7	(19.0)	8.1	(9.1)	9.5	(14.7)	7.6	(7.4)	18.2	(33.0)
Water heating use	WH	Daily water heating energy use, kWh/day	2.0	(0.5)	2.0	(0.5)	2.0	(0.5)	2.0	(0.4)	2.2	(0.5)
Dwelling size	DSIZE	Surface, m^2	113.9	(146.4)	115.9	(100.7)	109.7	(120.4)	96.3	(50.9)	135.2	(247.7)
Dwelling type	DTYPE	1. Single family house, 2. Terraced house, 3. Multi-family house, 4. Apartment block (> 10 dwellings)	2.4	(1.4)	2.7	(1.4)	2.6	(1.5)	2.5	(1.3)	1.7	(1.1)
Period of construction	CONSTR	1. Before 1900, 2. 1900-1945, 3. 1945-1970, 4. 1970-1990, 5. 1990-2000, 6. After 2000	4.2	(1.3)	4.6	(1.1)	4.4	(1.1)	4.2	(1.2)	3.5	(1.6)
Electricity production	EPROD	Share of respondents who produce electricity	0.04	(0.19)	0.02	(0.14)	0.02	(0.13)	0.04	(0.19)	0.07	(0.26)
Refurbishment	REFURB	Quality of thermal insulation, 7-point scale: 1. Very bad, 7. Very good	4.6	(1.7)	4.3	(1.8)	5.1	(1.6)	4.1	(1.8)	5.1	(1.5)
Attitude energy initiative	EINI_ATT	Attitude towards energy cooperatives, 7-point scale: 1. Very negative, 7. Very positive	5.1	(1.6)	5.6	(1.4)	4.9	(1.6)	5.1	(1.6)	4.8	(1.7)
Use energy initiative	EINI_USE	Use of energy cooperatives, 7-point scale: 1. Very negative, 7. Very positive	2.1	(1.8)	2.1	(1.8)	3.0	(1.9)	1.9	(1.6)	1.8	(1.5)
Urban-rural context	RURAL	1. Urban, 2. Sub-urban, 3. Rural	1.61	(0.80)	1.57	(0.77)	1.49	(0.81)	1.42	(0.65)	2.00	(0.87)
Household size	HHSIZE	No. household members	2.93	(1.91)	3.28	(2.82)	3.03	(1.59)	3.03	(1.20)	2.28	(1.07)
Female	FEMALE	Share of female respondents	0.62	(0.49)	0.70	(0.46)	0.60	(0.49)	0.60	(0.49)	0.55	(0.50)
Age	AGE	No. years	40.1	(15.6)	34.9	(13.4)	31.5	(12.2)	40.1	(13.6)	53.3	(14.3)
Education	EDUC	1. No education, 2. Primary school, 3. Secondary school, 4. High school, 5. Vocational school, 6. University degree	5.07	(1.14)	5.42	(0.90)	4.87	(0.98)	5.21	(1.00)	4.63	(1.46)
Married	MARRIED	Share of married respondents (relationship status)	0.52	(0.50)	0.37	(0.48)	0.44	(0.50)	0.59	(0.49)	0.69	(0.46)
Income	INCOME	Monthly net household income: 1. < €600, 2. €601-1500, 3. €1501-3000, 4. €3001-4500, 5. €4501-6000, 6. > €6000. RO sample: 1. < €176, 2. €177-330, 3. €331-552, 4. €553-882, 5. €883-1214, 6. > €1214	3.10	(1.09)	2.99	(0.93)	3.41	(1.36)	2.95	(1.01)	3.21	(1.08)
Working time	WHRS	1. < 20 h/week, 2. 20-40 h/week, 3. 40-60 h/week, 4. > 60 h/week	2.94	(1.06)	3.05	(1.06)	3.10	(1.05)	2.67	(1.07)	3.00	(0.99)

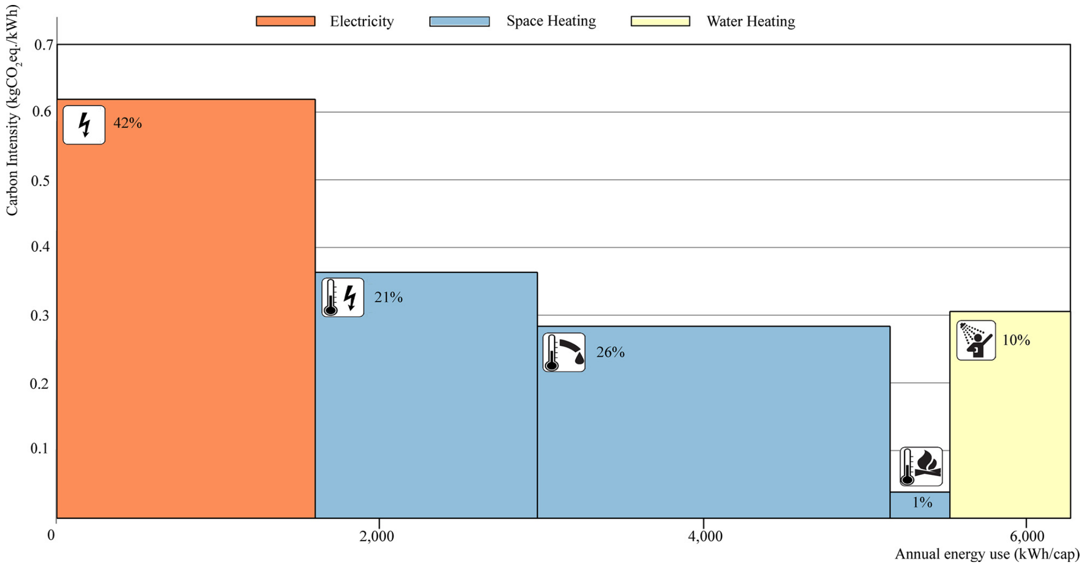

Fig. 2. Electricity, space heating and water heating showing carbon intensities (in $kgCO_2eq/kWh$) and energy use (in kWh). The area of each rectangular depicts the CF and the %s - the footprint share of shelter CF (all summing to 100%). Space heating by electricity and district heating, by oil and gas, and by renewables (pellets/firewood or solar-thermal heater) and heat pump (from left to right).

7 kW h/cap, respectively. Water heating contributed to about 10% and 12% of annual shelter CF and energy use, respectively. Water heating is more relevant in low-energy buildings, where energy use for heating is drastically reduced (Roux et al., 2016).

2.3. Regression model

We conducted linear multivariate regression analyses with behavior and carbon intensity of behavior as dependent variables (individual level). For mobility, we explored explanatory factors behind the carbon intensity of land and air travel (in $grCO_2eq/pkm$), and travel distance (in km/day). For shelter, we examined the factors behind energy use (in kWh/day) and its carbon intensity (in $grCO_2eq/kWh$). Intensities were set to zero for the zero-footprint cases. Distance and energy use enter the model in linear terms (instead of logarithmic) in order to keep the zero observations (e.g. those who do not fly).

We further explored the choice of transport mode and heating source, which had direct implications for the carbon intensity of mobility and shelter. We performed a pooled multinomial logit model (MLOGIT) to assess the likelihood (probability) of opting for a specific transport or heating mode. MLOGIT is suitable when the dependent variable is categorical and cannot be ordered (Fan et al., 2007; Pforr, 2014). We performed MLOGIT on a trip rather than individual level (long format) for mobility as individuals generally reported multiple regular trips. We further fit a MLOGIT with fixed effects (FE) accounting for the unobserved heterogeneity where individuals reported the regular use of several transport modes (SI table 17). We reported marginal effects (Tables 3 and 5) depicting the predicted probabilities of belonging to one of the dependent variable outcomes and the predicted changes in probabilities resulting from changes in the independent variables.

The regression approach allows for the investigation of effects in isolation. However, the change in one factor important for the CF may be associated with a change in other factors as well. For example, the carbon savings achieved from urbanization may be reduced or even removed altogether in the case of higher income levels or smaller household sizes (e.g. see Ottelin et al., 2015). We used the marginal effects results to explore combined effects of selected highly correlated factors (Table 2) on the CF (Tables 4 and 6), setting all other factors to mean levels. For odds ratios of pooled and FE MLOGIT, as well as food- and clothing-specific footprint determinant analysis, see SI “Results”.

Variable selection was informed by prior literature and survey design. In the mobility-specific regressions, we controlled for travel distance, purpose of travel (work/private), car ownership, and attitudes and use of ride sharing and car sharing initiatives and platforms. In shelter-specific regressions, we controlled for energy use, dwelling characteristics, attitudes and use of energy cooperatives. As we incorporated a large number of independent variables, we additionally performed tests for multicollinearity, or the potential for instability of the coefficients and their “inflated” variance (Belsley et al., 1980; Chen et al., 2003). We reported variance inflation factor (VIF) and tolerance values in SI table 16, which pointed to no strong evidence for multicollinearity.

3. Results

Table 1 outlines descriptive statistics and definitions of all variables which enter the regression models. An analysis of the pairwise correlation coefficients and their significance is presented in Table 2. The correlation table highlights where more caution is needed to interpret regression coefficients. It can also be useful for profiling, e.g. classifying respondents who use mobility- and energy- initiatives.

3.1. Mobility

The total carbon intensity model has high values of Adjusted R^2, 0.28. The distance models have lower Adjusted R^2, between 0.03 and 0.04 (Table 3). The pooled MLOGIT model reported a Pseudo R^2 of 0.17.

3.1.1. Distance and travel characteristics

The longer the distance, the less likely the travel is active. A one-kilometer increase in the distance of the daily trip decreases the probability of walking or biking by 1.2% on average. The percentage change

Table 2
Pairwise correlation coefficients of explanatory variables. Bold values indicate 99% significance, italic values indicate 95% significance, and the rest are insignificant.

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
CAR_ONE	1	1.00																		
CAR_MANY	2	**−0.75**	1.00																	
MINI_ATT	3	−0.03	−0.02	1.00																
MINI_USE	4	**−0.07**	**0.08**	**0.28**	1.00															
DSIZE	5	0.02	0.04	−0.03	−0.01	1.00														
DTYPE	6	**−0.10**	−0.00	0.03	0.03	**−0.22**	1.00													
CONSTR	7	0.02	0.01	−0.05	**−0.08**	**−0.07**	**0.07**	1.00												
EPROD	8	−0.00	0.04	−0.04	−0.02	**0.09**	**−0.10**	0.03	1.00											
REFURB	9	0.04	0.01	**−0.09**	−0.05	*0.06*	−0.04	*0.05*	0.05	1.00										
EINI_ATT	10	**−0.09**	0.04	**0.51**	**0.17**	−0.01	*0.05*	0.01	−0.01	−0.05	1.00									
EINI_USE	11	**−0.07**	−0.00	0.03	**0.46**	0.04	0.03	−0.01	0.05	*0.05*	**0.20**	1.00								
RURAL	12	*0.06*	*0.05*	*−0.06*	**−0.06**	**0.21**	**−0.51**	−0.04	**0.11**	*0.05*	**−0.07**	−0.01	1.00							
HHSIZE	13	**−0.17**	**0.20**	0.01	0.04	**0.09**	**−0.08**	**0.07**	0.01	−0.04	*0.05*	0.05	**0.07**	1.00						
FEMALE	14	**−0.13**	**0.09**	*0.06*	0.02	−0.02	0.03	0.04	0.01	−0.01	0.04	0.01	0.01	*0.05*	1.00					
AGE	15	**0.18**	−0.03	**−0.07**	**−0.19**	0.03	**−0.10**	**−0.22**	**0.07**	**0.15**	**−0.11**	**−0.13**	**0.10**	**−0.26**	**−0.17**	1.00				
EDUC	16	**0.09**	−0.02	**0.12**	−0.00	*−0.06*	**0.12**	0.05	−0.02	−0.04	**0.13**	**−0.07**	**−0.16**	−0.03	−0.04	0.01	1.00			
MARRIED	17	0.03	**0.13**	−0.09	−0.15	*0.06*	**−0.10**	*-0.05*	**0.07**	**0.16**	**−0.10**	**−0.08**	**0.10**	0.03	**−0.11**	**0.44**	0.01	1.00		
INCOME	18	**0.08**	0.05	−0.02	**−0.10**	**0.13**	**−0.08**	0.01	*0.06*	**0.19**	0.01	−0.04	0.04	**0.12**	**−0.09**	**0.15**	**0.19**	**0.27**	1.00	
WHRS	19	**−0.17**	0.04	−0.04	**0.07**	0.04	−0.04	0.00	0.02	0.03	0.00	**0.08**	**0.08**	*0.06*	0.02	**−0.17**	**−0.23**	**−0.21**	**−0.17**	1.00

decreases with rising distance non-linearly (Fig. 3), where an increase from 5 to 10 km per return trip reduces active travel by 6.8%, from 10 to 15 km by only 5.9%, and so on. Thus, lowering distances widens the travel mode choice (see also Chapman et al., 2016; Pucher and Buehler, 2006; Quinn et al., 2016). There is a slight increase in the likelihood of opting for public transport (0.5%) with one-km distance rise, though public travel is less susceptible to changing distance (Table 3). Work trips (or regular commuting) are associated with a 6% higher probability of occurring via public transport (Table 3), at 16.7% and 23.2% for private and work respectively. We do not control for potential explanatory factors such as time of travel (e.g. rush hours and traffic), opportunity for ride-sharing, or the role of affective and instrumental factors for trips (e.g. see Anable and Gatersleben (2005)).

Car owners have higher carbon intensity of travel, 64 and 34 grCO_2eq/pkm for single- and multi-users, respectively (Table 3). On average, sole users of cars are 49.3% more likely to drive compared to those who do not own a car (Table 3), with a high probability of driving even for short trips. The likelihood of driving for daily return trips at 5 km is 46.9% (Fig. 3). Car ownership is not associated with changes in travel distance. While car ownership has influenced travel distances and urban planning historically (e.g. the Marchetti Constant (Newman and Kenworthy, 2006)), the effect may be less important in a cross-sectional study controlling for urban-rural typology. We also find that car ownership and use increase the likelihood of having car trips for both work and private (SI table 18). For the sub-sample with positive number of car trips, being a single- and multi-user is associated with an increase in the annual number of car private trips by 89 and 72, respectively, but had no effect on the number of work trips.

Naturally, flying is associated with higher total carbon intensity (Table 3), where an increase by one return short flight annually is associated with a rise of 8 grCO_2eq/pkm. Car owners show no difference in flying. Previously, car-free households have been shown to have somewhat higher air transport emissions, reflecting higher income levels (Ornetzeder et al., 2008; Ottelin et al., 2017).

3.1.2. Attitudes and use of initiatives

Table 3 provides no clear evidence that use of car- and ride-sharing initiatives translate into lower mobility behavior and footprint. Instead, we find a positive coefficient for land distance. It should be noted, however, that this is the effect keeping car ownership and urban-rural typology constant. Table 2 points to a negative correlations with car ownership (-0.07) and rural context (-0.06), both of which significant at the 99%. This is in support of prior findings that car-sharing facilities enable a reduction in vehicle ownership (Schanes et al., 2016).

More favorable attitudes towards ride- and car-sharing initiatives are associated with a decrease in the carbon intensity of land travel and likelihood of driving (Table 3). Nevertheless, attitudes are of little relevance for the distance travelled by air and land (in line with Alcock et al., 2017). From a psychological perspective, the result can be interpreted by the autonomy of motivations that stimulate a certain behavior (Hartig et al., 2001; Ryan and Deci, 2000).

3.1.3. Urban-rural typology and household size

The likelihood of active travel rises with population density, on average 30.6% for urban and 23.2% for rural context (in line with Pucher and Buehler, 2006; Quinn et al., 2016). A similar decrease is noted for public transport, an average of 2.7% (Table 3). Similarly, prior studies have noted that population growth in low-density suburban areas results in more commuting via passenger vehicles (Dodman, 2009; Jones and Kammen, 2014; Rosa and Dietz, 2012). Furthermore, the shift to rural living is associated with an increase in the travel distance by land ($\beta = 5.03$, $p < .01$).

Household size is insignificant in determining the travel intensity and distance (see also Ivanova et al., 2017). This points to the lack of household economies of scale for land- and air-based travel, e.g. due to differences in travel routines and preferences within the household.

Table 3
Multiple linear regressions (b/se) with total carbon intensity (in $grCO_2eq/pkm$) and daily travel distance (in km). Marginal effects from pooled MLOGIT with land-based transport mode as dependent variable. Independent variables measured per return trip (for variables in italic) and individual (for other variables). WORK is a binary variable with a value of 1 for work and 0 for private trips. Regional controls and robust standard errors included. *p < .1, ** p < .05, *** p < .01.

Mobility	Distance			Carbon intensity	Land-travel marginal effects		
	Total	Land	Air	Total	Active	Public	Private motorized
LMOB_DIS (km/day)				**−0.609*** **	***−0.012**** ***	***0.005**** ***	***0.008**** ***
				(0.13)	***(0.001)***	***(0.001)***	***(0.001)***
LMOB_DIS sq.				0.001	***0.000**** ***	***−0.000**** ***	***−0.000**** ***
				(0.00)	***(0.000)***	***(0.000)***	***(0.000)***
AMOB_SHORT				**8.390*** **			
				(1.03)			
WORK					*0.023**	***0.063**** ***	***−0.086**** ***
					(0.014)	***(0.012)***	***(0.016)***
CAR_ONE	1.040	2.217	−1.526	**63.636*** **	**−0.209*** **	**−0.284*** **	**0.493*** **
	(5.35)	(3.22)	(4.30)	**(6.76)**	**(0.026)**	**(0.021)**	**(0.034)**
CAR_MANY	−0.104	1.845	−2.415	**34.219*** **	**−0.150*** **	**−0.162*** **	**0.311*** **
	(5.26)	(3.12)	(4.20)	**(6.78)**	**(0.026)**	**(0.020)**	**(0.036)**
MINI_ATT	0.012	−0.569	0.594	−0.572	0.007	0.007*	**−0.014*** **
	(0.89)	(0.58)	(0.62)	(1.13)	(0.005)	(0.004)	**(0.005)**
MINI_USE	**3.251** **	**1.345** **	1.891*	0.504	0.004	−0.007*	0.002
	(1.34)	**(0.62)**	(1.10)	(1.01)	(0.004)	(0.004)	(0.005)
RURAL	3.641*	**5.029*** **	−1.418	**11.256*** **	**−0.037*** **	**−0.027*** **	**0.063*** **
	(1.89)	**(1.32)**	(1.30)	**(2.36)**	**(0.009)**	**(0.009)**	**(0.010)**
HHSIZE	−1.709	−0.614	−1.081*	−0.844	**0.006** **	−0.002	−0.004
	(1.07)	(0.74)	(0.63)	(0.91)	**(0.003)**	(0.003)	(0.004)
FEMALE	**−12.200*** **	**−6.440*** **	−5.792*	−0.842	−0.022	**0.044*** **	−0.022
	(3.79)	**(2.00)**	(3.02)	(3.63)	(0.014)	**(0.014)**	(0.017)
AGE	−0.179	−0.128*	−0.050	−0.179	0.001	**−0.002** **	0.001
	(0.12)	(0.08)	(0.09)	(0.15)	(0.001)	**(0.001)**	(0.001)
EDUC	**4.350** **	0.646	**3.794*** **	−0.854	**0.026*** **	**−0.013** **	−0.014*
	(1.73)	(0.98)	**(1.37)**	(1.73)	**(0.007)**	**(0.006)**	(0.008)
MARRIED	−2.756	−1.210	−1.381	**13.644*** **	**−0.032** **	−0.053*	**0.082** **
	(4.32)	(2.19)	(3.54)	**(3.87)**	**(0.016)**	(0.028)	**(0.019)**
INCOME	**6.630*** **	**2.720*** **	**3.865*** **	**5.869*** **	−0.011*	0.001	0.010
	(1.77)	**(1.05)**	**(1.33)**	**(1.88)**	(0.007)	(0.006)	(0.009)
WHRS	−2.161	−1.224	−0.900	**−4.053** **	0.011*	0.013*	**−0.025*** **
	(1.54)	(0.93)	(1.17)	**(1.79)**	(0.007)	(0.007)	**(0.008)**
Adjusted (Pseudo) R^2	**0.035**	**0.040**	**0.026**	**0.282**		**(0.172)**	
N individuals (N trips)	**1399**	**1409**	**1399**	**1399**		**1394 (4393)**	

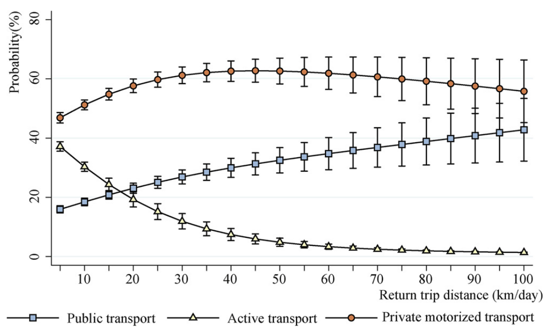

Fig. 3. Predictive margins with 95% confidence intervals calculated for the daily km predictor of the pooled MLOGIT. Y axis (probability %) and x axis (return trip distance km/day).

3.1.4. *Socio-demographics*

Females and younger respondents are more likely to opt for public transport (Table 3). Furthermore, females note 12 km/day lower travel distance, on average. Prior studies have pointed to the gender- and age-unequal distributions of time use, patterns of expenditure, and employment (Caeiro et al., 2012; Chancel, 2014; Pullinger, 2012; Quinn et al., 2016). Relationship status has a limited effect in explaining the CF of travel, although married respondents were 8.2% more likely to drive on average. The relationship status has implications for time use, working schedules and children dependency (Pullinger, 2012).

Individuals with higher education are more likely to travel actively and by air, and less likely to use public transport. Differences may be partially attributed to socioeconomic status, place of residence (Pucher et al., 2011; Whitfield et al., 2015), or higher awareness about co-benefits (e.g. health).

3.1.5. *Income and working time*

Income is an important determinant of distance travelled by both land and air, where a rise in income by one level brings about an increase in the average daily travel by 7 km/day. Our analysis confirms the mobility domain (and particularly air mobility) as income-elastic (Creutzig et al., 2015; Ivanova et al., 2017; Rosa and Dietz, 2012). The effect of working hours (in isolation of the income effect) is insignificant in most mobility models (Table 3). This has implications for policies that aim to reduce working hours, while keeping the same level of disposable income. Furthermore, longer working hours (> 60 h/week) are associated with a decrease in carbon intensity, which is in line with prior hypothesis that very high work load may reduce participation in leisure and family travel (Czepkiewicz et al., 2018).

3.1.6. *Combined effects*

Table 4 explores the combined effect of urbanity, trip distance, car ownership, and mobility initiative use on the choice of transport mode and land-travel CF overall. Limiting the daily travel distance through compact urban environment may produce substantial footprint savings. For example, a 5-km average return trip (Case 1) is associated with an annual land-travel CF close to ten times lower than our sample's average. However, in order to realize the full benefit from urbanization

Table 4
Land trip characteristics based by case. The annual carbon footprint is calculated assuming trip distance is travelled daily. The table presents the fixated levels for regressors, and in bold– the estimated values for choice of transport, carbon intensity and footprint based on the marginal effects regression in Table 3. The estimated values assume mean levels for all other regressors in the model.

Land travel (Mobility)	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
RURAL	Urban	Urban	Urban	Urban	Rural	Rural
LMOB_DIS (km/return trip)	5	10	10	20	20	30
CAR_ONE	No	No	Yes	Yes	No	No
CAR_MANY	No	No	No	No	Yes	Yes
MINI_USE	Always	Always	Never	Never	Never	Never
Active transport share	**0.51**	**0.43**	**0.18**	**0.08**	**0.12**	**0.08**
Carbon intensity ($kgCO_2eq/pkm$)	**0.09**	**0.10**	**0.12**	**0.20**	**0.18**	**0.19**
Annual carbon footprint (tCO_2eq/cap)	**0.2**	**0.4**	**0.7**	**1.5**	**1.3**	**2.1**

and reduced distance, there needs to be proportionate changes in car use and ownership (e.g. Case 2–3, Case 4–5).

Furthermore, there is a strong negative correlation between the car ownership and use of mobility initiative variables (Table 2). The more frequent use of mobility initiatives may increase travel distance, holding car ownership constant (Table 3); however, the use of such initiatives may also reduce car ownership rates. Table 4 signals for the substantial difference in emissions and active travel that may occur through the use of car sharing initiatives (e.g. Case 2–3).

3.2. Shelter

The regression models on the total energy use have a high Adjusted R^2, 0.77 (Table 5), with varying model fit for daily electricity, space and water heating use models, 0.10, 0.84 and 0.57, respectively. The total carbon intensity model has an Adjusted R^2 of 0.27. The choice of space heating, particularly, is explored through the marginal effects model with a Pseudo R^2 of 0.24. The choice of water heating sources is much less explained through our model with a Pseudo R^2 of 0.13 (see SI table 19).

3.2.1. Energy use and dwelling characteristics

An increase of electricity use by 1 kW h/day raises the likelihood of electricity-powered space heating by an average of 0.6%, explaining the noted increase in the total carbon intensity of energy use (Table 5). Own electricity production (EPROD) is insignificant for energy use suggesting that producing own electricity does not necessarily increase its use.

Space heating needs play a significant role for the choice of heating source. Particularly, a rise in the daily space heating by 1 kW h raises the probability of heating by fossil fuel with 0.8% on average and reduces the probability of heating by district heating by the same amount. The effect on renewables is only partially significant. While lowering space heating needs may reduce reliance on fossil fuels, such efforts should be coupled with strong incentives for a transition to renewable heating sources and efforts to utilize local energy sources such as waste heat and energy-from-waste technologies (Lausselet et al., 2016; UNEP, 2015). Water heating needs have little relevance for the choice of space and water heating source.

Larger dwellings use more energy for space heating. An increase in the dwelling size by $1m^2$ brings about a rise in space heating needs by 0.1 kW h/day (or 41 kW h/year). However, larger dwelling have also lower carbon intensity (a reduction of 0.15 $grCO_2/kWh$ per m^2), being more likely to be heated by renewables or district heating (Table 5). District heating is in general a cost-competitive and cheap option to provide heat. Yet, district heating - and renewable electricity production - have high capital expenditure and relative low operating cost (UNEP, 2015), making them more suitable for larger dwellings.

Apartments are associated with lower energy use (3.1 kW h/day less compared to single family home), particularly electricity and space heating (keeping dwelling size constant). However, apartment blocks have higher carbon intensity per kWh, 62 $grCO_2eq/kWh$ more compared to single family home. This increase in intensity is due to changes in heating source (less renewables/heat pump, more district heating) with the effect being highly significant for both space and water heating. District heating is not well suited for single-building options with its cost structure (UNEP, 2015). Dwelling type and urban-rural typology are highly correlated (-0.51), with houses being more likely located in rural areas, and apartments in urban areas.

Newer dwellings have lower space heating needs, but higher electricity consumption and, hence, higher carbon intensity per unit of energy use. Prior assessments of new constructions have found that energy savings per m^2 are generally offset by changes in user heating habits and the amount of energy appliances (EEA, 2016; Sandberg et al., 2016b). We find a strong pairwise correlation between age of dwelling and inhabitants (-0.22) pointing to younger inhabitants opting for newer dwellings (Table 2); that is, the effect of electricity use may be explained variation in consumption patterns among age cohorts. The construction decade has no significant effect on the choice of space or water heating.

Similarly, higher level of refurbishment reduces space heating needs; the shift in the quality of thermal insulation from “very bad” to “very good” is associated with a drop in space heating consumption by 11 kW h/day (or 4 MW h/year). Energy reductions potentials are directly linked to refurbishment rates (IWU, 2013), with refurbishment rates across 11 European countries varying between 0.6–1.6% (Sandberg et al., 2016a). At the same time, better thermal insulation is associated with a higher likelihood of opting for oil or gas space heating and, hence, higher carbon intensity; particularly the shift from “very bad” to “very good” increases the likelihood of heating by fossil fuels by 12%.

3.2.2. Attitudes and use of initiatives

Finally, attitudes and use of energy cooperative initiatives are of no significance for the annual energy needs (see Diekmann and Preisendörfer, 2003). The use of energy cooperatives is associated with lower likelihood of not heating (Table 5). Those who frequently use energy cooperative initiatives (“Always”) are 6% more likely to heat water by electricity, suggesting a possible moral licensing effect (Tiefenbeck et al., 2013), and 13.8% less likely to heat by fossil fuels, than those who never use such initiatives.

3.2.3. Urban-rural typology and household size

We find the effect of rural typology to be insignificant for energy use. This effect is likely influenced by the high correlation between urban-rural typology and dwelling type in European context (Table 2). Furthermore, rural dwellings are more likely to be heated by renewables. The use of firewood is more common to rural areas due to the close supply (Euroheat and Power, 2006). Common heating solutions in urban areas have a line-based network energy supply as natural gas and

Table 5
Multiple linear regressions (b/se) with total carbon intensity (in $grCO_2eq/kWh$) and daily energy use (in kWh) as dependent variables. Marginal effects from the pooled MLOGIT with space heating source as dependent variables with unit of analysis – an individual. We only perform marginal effects for those that have selected a single heating source (81%). Regional controls and robust errors included in all models. *p < .1, ** p < .05, *** p < .01.

	Energy use				Carbon intensity	SH marginal effects				
	Total	ELEC	SH	WH	Total	Electricity	District heating	Oil/gas	Renewables/ heat pump	Not Heating
ELEC (kWh/day)					**5.993*** **	**0.006*** **	−0.002	−0.000	−0.000	−0.003*
					(1.31)	**(0.001)**	(0.004)	(0.004)	(0.002)	(0.002)
SH (kWh/day)					0.372	0.002	**−0.009*** **	**0.008*** **	−0.002*	0.001
					(0.43)	(0.002)	**(0.003)**	**(0.003)**	(0.001)	(0.001)
WH (kWh/day)					−16.357*	0.005	0.050	−0.091*	0.019	0.018
					(9.90)	(0.028)	(0.031)	(0.053)	(0.035)	(0.013)
DSIZE	**0.112*** **	0.001	**0.112*** **	−0.000*	**−0.150** **	−0.001	**0.001*** **	−0.000	**0.000*** **	0.000
	(0.01)	(0.00)	**(0.01)**	(0.00)	**(0.06)**	(0.000)	**(0.000)**	(0.000)	**(0.000)**	(0.000)
DTYPE	**−1.029*** **	**−0.353** **	**−0.673*** **	−0.002	**19.103*** **	−0.006	**0.036*** **	−0.007	**−0.032*** **	**0.008** **
	(0.26)	**(0.14)**	**(0.20)**	(0.01)	**(2.33)**	(0.007)	**(0.009)**	(0.012)	**(0.008)**	**(0.004)**
CONSTR	**−1.834*** **	**0.219** **	**−2.052*** **	−0.001	**9.958*** **	−0.000	−0.010	0.007	−0.001	0.004
	(0.23)	**(0.10)**	**(0.20)**	(0.01)	**(2.25)**	(0.008)	(0.008)	(0.012)	(0.007)	(0.004)
EPROD	1.079	0.682	0.398	−0.001	−20.669	0.077	−0.080	0.201*	0.087*	**−0.284*** **
	(1.37)	(0.79)	(0.99)	(0.03)	(14.70)	(0.063)	(0.103)	(0.109)	(0.047)	**(0.048)**
REFURB	**−1.792*** **	−0.044	**−1.752*** **	0.004	**8.258*** **	−0.005	−0.009	**0.020** **	−0.010*	0.002
	(0.17)	(0.13)	**(0.10)**	(0.01)	**(1.68)**	(0.006)	(0.007)	**(0.009)**	(0.005)	(0.003)
EINI_ATT	−0.280	−0.244*	−0.038	0.001	−0.005	−0.000	−0.010	0.004	0.004	0.002
	(0.20)	(0.14)	(0.13)	(0.01)	(1.68)	(0.006)	(0.006)	(0.009)	(0.005)	(0.003)
EINI_USE	0.051	−0.041	0.091	0.001	2.491	0.000	0.009*	−0.005	0.001	**−0.006** **
	(0.15)	(0.06)	(0.12)	(0.00)	(1.59)	(0.005)	(0.005)	(0.008)	(0.004)	**(0.003)**
RURAL	−0.139	0.062	−0.177	−0.024*	**−16.62*** **	−0.016	0.011	**−0.048** **	**0.063*** **	−0.011
	(0.44)	(0.18)	(0.38)	(0.01)	**(3.95)**	(0.014)	(0.015)	**(0.020)**	**(0.010)**	(0.009)
HHSIZE	**−2.825*** **	**−0.475*** **	**−2.186*** **	**−0.164*** **	−0.196	0.004	0.013	−0.023	0.005	0.000
	(1.00)	**(0.16)**	**(0.80)**	**(0.06)**	(1.99)	(0.007)	(0.007)*	(0.016)	(0.006)	(0.003)
FEMALE	0.978*	0.000	**0.982** **	−0.005	2.843	−0.017	−0.021	0.045*	−0.019	0.011
	(0.58)	(0.35)	**(0.44)**	(0.02)	(5.38)	(0.018)	(0.019)	(0.027)	(0.016)	(0.011)
AGE	**0.105*** **	**0.036*** **	**0.061** **	**0.007*** **	0.119	−0.001	0.001	0.002	−0.001	−0.001
	(0.04)	**(0.01)**	**(0.03)**	**(0.00)**	(0.22)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
EDUC	−0.259	−0.010	−0.269	**0.020*** **	−1.002	−0.007	−0.004	0.008	0.005	−0.003
	(0.28)	(0.20)	(0.18)	**(0.01)**	(2.43)	(0.009)	(0.008)	(0.012)	(0.008)	(0.004)
MARRIED	**−3.035*** **	**−0.789** **	**−1.936*** **	**−0.310*** **	−7.299	−0.005	**−0.064*** **	**0.085*** **	−0.008	−0.008
	(0.92)	**(0.34)**	**(0.72)**	**(0.05)**	(6.67)	(0.022)	**(0.025)**	**(0.032)**	(0.019)	(0.014)
INCOME	−0.206	0.177	−0.361	−0.022*	0.997	0.003	0.004	0.027*	−0.016*	**−0.017*** **
	(0.30)	(0.12)	(0.24)	(0.01)	(3.15)	(0.011)	(0.010)	(0.014)	(0.009)	**(0.006)**
WHRS	−0.360	−0.081	−0.257	**−0.022*** **	−2.569	−0.002	−0.015	0.008	0.009	0.000
	(0.23)	(0.14)	(0.17)	**(0.01)**	(2.54)	(0.009)	(0.009)	(0.014)	(0.008)	(0.005)
Adjusted (Pseudo) R^2	**0.766**	**0.104**	**0.844**	**0.565**	**0.269**			**(0.237)**		
N individuals	**1407**	**1407**	**1407**	**1407**	**1407**			**1133**		

district heating, requiring a certain heat demand density to justify investment (Euroheat and Power, 2006).

The household scale effect is substantial for energy needs. A rise in the household size of one member is associated with a drop of individual electricity, space and water heating needs by 0.5, 2.2 and 0.2 kW h/day (or about 170, 800 and 60 kW h/year), respectively (Table 5). This effect is driven by shared consumption of heating, cooling and light, as well as common use of electrical appliances (Liu et al., 2003; Rosa and Dietz, 2012). The co-housing model emerges as a cost-competitive social innovation that may further inspire a restructuring of the social institution of housing and technological innovations (Seyfang and Smith, 2007).

3.2.4. Socio-demographics

Females have 360 kW h/cap higher annual space heating needs, although the effect is only partially significant for total energy use. Age has a positive effect on energy needs, ceteris paribus. An additional year brings about an increase in the annual electricity, space heating and water heating needs by 13, 22 and 3 kW h/cap, respectively. Education is of no significance for the total energy needs or heating source.

Married people have substantially lower energy needs, about 3 kW h/day (or 1095 kW h/year). A possible explanation is the effect of household composition beyond the household size, e.g. having children. Married respondents were 8.5% more likely to opt for fossil fuels and 6.4% less likely to heat by district heating. Being married was noted to be highly positively correlated with age (0.44), income (0.27) and refurbishment level (0.16), and negatively correlated with working hours (-0.21).

3.2.5. Income and working time

We find energy use to be income inelastic (Table 5); this effect is in line with prior findings, similar to other basic needs (see Ivanova et al., 2017). That being said, higher income is associated with a lower likelihood of not heating. This suggests that financial savings may be a primary reason for not heating, calling attention to the potential of energy poverty-related cold housing rising with energy prices (Ürge-Vorsatz et al., 2014). Differences in the working time are of little relevance for the shelter footprint.

Table 6
Space heating characteristics by case. The table presents the fixated levels for regressors, and in bold – the estimated values for choice of heating mode, carbon intensity and footprint based on the marginal effects regressions in Table 5. The estimated values assume mean levels for all other regressors in the model.

Space heating (Shelter)	Case 7	Case 8	Case 9	Case 10	Case 11	Case 12
RURAL	Urban	Urban	Urban	Rural	Rural	Rural
SH (kWh/day)	11	11	17	26	19	22
DSIZE	60	100	100	160	100	90
DTYPE	Apartment block	Apartment block	Single family home	Single family home	Single family home	Single family home
HHSIZE	2	4	2	4	4	2
Oil and gas share	**0.67**	**0.62**	**0.71**	**0.59**	**0.57**	**0.65**
Carbon intensity (kgCO_2eq/kWh)	**0.33**	**0.33**	**0.31**	**0.24**	**0.26**	**0.27**
Annual carbon footprint (tCO_2eq/cap)	**1.3**	**1.3**	**2.0**	**2.2**	**1.7**	**2.1**

3.2.6. Combined effects

According to Table 5, rural dwellings are more likely to be heated by renewables compared to urban dwellings and are, thus, less carbon intensive. Rural dwellings are also generally associated with larger sizes and single family house-types (higher heating needs), and larger household sizes (lower heating needs). There is a significant potential for carbon savings with the shift to urban and compact environment, e.g. 24% difference in the space heating footprint between Case 8 and Case 11 (Table 6). Nevertheless, dwelling characteristics and household size should also be considered to realize the potential benefits, in both urban (e.g. Case 8–9) and rural (e.g. Case 10–12) context.

3.3. Other consumption

No major increases in other consumption are noted on domain level according to the food- and clothing-specific regression results with regards to the effects discussed above. Instead, we find pro-environmental behaviors to be consistent across domains, with food- and clothing-related emission decreases associated with pro-environmental action in the shelter or mobility domains. The models have Adjusted R^2 values of 0.28 and 0.20, respectively (SI table 20).

The shift from individualized motor transport to active or public transport does not relate to emission increases in other consumption domains. On the contrary, a 10% rise in active transport share is associated with a 1% drop in food-related emissions, which may be related to overall health awareness or concern. Car ownership and air travel are also associated with higher emissions in other consumption.

The use of electricity and space heating is positively related to food and clothing footprints. Own electricity production is associated with a drop in other consumption. The effect of construction decade is more ambiguous with newer dwellings having lower heating needs and higher food CF, which may be due to socio-economic differences among inhabitants. The shift to urban living has no significant effect on other consumption, while lower income and more favorable attitudes towards energy cooperatives are associated with drops in food and clothing footprints.

3.4. Limitations

We discuss uncertainty with regards to some of the assumptions made for footprint calculations and validate our estimates and assumptions with prior studies and uncertainty ranges (see SI “Footprint uncertainty and validation”).

Prior studies discuss the importance of under-reporting in consumption and expenditure surveys of irregular and small purchases (Bee et al., 2012; Ivanova et al., 2017) and more specifically of fuel consumption (Ottelin et al., 2017). Studies emphasize the error and uncertainty in the data collected in travel surveys and provide evidence for under-reporting, e.g. 10–15% and up to 50% for certain types of trips (Clarke et al., 1981). Particularly, off-peak trips and trips for non-work purposes seem to be associated with higher measurement error and incomplete recall and reporting of travel (Clarke et al., 1981; Giesbrecht et al., 2004; Minnen et al., 2015). Minnen et al. (2015) find an average day-to-day variability of travel (as % of total variability) of 60%, varying between 46.7% for work and 75.7% for leisure, family- and friends-related travel, suggesting that travel is not very stable across weekdays. Furthermore, our survey covers only regular land-based travel and systematically disregards impacts embodied in irregular travel. The link to our survey was distributed between the winter months of December 2015 and February 2016, which may have contributed to some season-specific consumption recording. Jara-Díaz and Rosales-Salas (2015) discuss measurement issues with survey responses recorded in a single day. To evaluate the accuracy of our estimates, we validated the bottom-up car trip data with annual mileages where available. We found that 40% of our bottom-up estimates were within the annual mileage range provided by respondents. About 16% of car-users had bottom-up car travel distance that was more than 5000 km higher than their annual mileage.

In terms of sample selection, our sample may suffer from self-selection. We discuss representativeness of the geographic samples with regards to observed socio-demographics; however, we could not control for other potentially important indicators for survey response, e.g. environmental concern. Hence, the point of our analysis is not to establish causal relationships, but rather to explore the role of technical and social factors hypothesized by prior literature (see SI “Model background”) in explaining observed differences in emission variance and choice of transport and heating.

Our regression analysis focuses on factors that vary within geographic regions that have been previously suggested as important for mobility and shelter impacts. We expect that there are additional macro-level factors (e.g. as suggested by Ivanova et al. (2017)) that our model disregards, such as geographical factors, resource availability, social and cultural norms and market prices. While we cannot measure the isolated effect of these factors on mobility and shelter, we include regional fixed effects to account for their combined effect. There may, however, be other relevant factors that vary within regions (e.g. neighborhood location, infrastructure and connectivity) that we do not consider due to survey design limitations.

Furthermore, we explore the choice of heating and travel mode as explained by energy use and distance. Nevertheless, it could be that the effect runs in the opposite direction as well. For example, one could use more electricity if it is also the heating source. Or, the level of thermal insulation could be decided post the choice of heating mode. Mutual causality was beyond the scope of our statistical considerations.

We include attitudinal indicators related to mobility- and shelter-initiatives in order to contribute to the limited literature (Moser and Kleinhückelkotten, 2017) exploring the role of psychological variables from impact-oriented perspective. However, our attitudinal questions do not cover broader and relevant consumer attitudes on energy, transportation, consumption, environment and environmental issues etc., and, thus, should not be interpreted as capturing the relevance of consumer attitudes for mobility and shelter carbon impacts overall. Furthermore, while we control for the use of sustainability-focused initiatives, we do not look specifically into initiative membership, which may have wider implications for sustainability transformations (Akenji, 2014; O'Brien, 2015).

Finally, we observe effects on a broad domain level of other consumption in the context of rebound concerns. This is done to provide a wider perspective on the observed effects in terms of various consumption. Nevertheless, our analysis as a snapshot of behaviors and impacts is limited in capturing income rebound resulting from monetary savings and system-wide effects (Druckman et al., 2011; Wood et al., 2017). For example, while we can compare other consumption impacts of car-free and car-using households, we cannot confirm that the potential emission differences result from monetary savings. The design of such analysis would require additional considerations, e.g. experimental setting and omitted selection threats to validity (Ottelin et al., 2017), specific abatement intervention (Chitnis et al., 2013; Druckman et al., 2011), consumption coverage detail (Ottelin et al., 2017), temporal dimension (Ottelin et al., 2018), consideration of direct rebound (Chitnis et al., 2013), differences in emission intensities (Chitnis et al., 2013; Druckman et al., 2011; Wood et al., 2017), re-spending, savings and economy-wide effects (Chitnis et al., 2013; Druckman et al., 2011; Hertwich, 2005; Wood et al., 2017).

4. Policy implications

Some differences occur in terms of the driving forces behind behaviors (consumption patterns) and their carbon intensities. Particularly, distance is influenced by socio-demographics and use of energy co-operatives, while the carbon intensity of travel by distance and car ownership. Both are influenced by the urban-rural context and income. Factors such as household size, age, and relationship status are important for energy use, while the amount of electricity used and income are important for the carbon intensity of shelter. Dwelling characteristics are important for both. We find the parallel analysis of determinants to uncover potentially offsetting effects, e.g. where attempts to lower the energy use in the dwelling may also impact the choice of heating.

We summarize the effects and list some policy-relevant considerations for carbon impact mitigation associated with these effects (Table 7). Table 7 should be interpreted as pointing to the places to intervene, rather than ranking potential interventions in terms of their effectiveness and upscaling potential. Different disciplines have proposed various interventions and policy instruments, and assessing their effectiveness for impact mitigation is beyond the scope of our study (e.g see Abrahamse et al., 2005; Creutzig et al., 2018). Considering additional co-benefits of proposed measures should also be regarded in the motivation of carbon mitigation policies (see SI "Co-benefits").

Highly populated areas can substantially reduce emissions at a low cost through more compact, connected and efficient design of housing and transport infrastructure. Particularly, we find that urban living is associated with lower travel by land and a higher active and public transport share, as well as smaller dwelling sizes and a larger share of apartment blocks. The "economies" of scale, proximity, and connectivity of urban areas enable the provision of infrastructure for active and public transport and the use policy instruments for environmental management (Dodman, 2009; Wiedenhofer et al., 2013). Our results underline the importance of shortening the travel distance for reducing transport emissions (directly and indirectly through the intensity of travel). Compact development and reductions in distance would be most enabling for active travel in the presence of proportionate reductions in travel time (e.g. Newman and Kenworthy, 2006). Furthermore, changes in car ownership and use of mobility sharing initiatives are needed to reap the full benefits from reduced distance.

Urbanization may reduce shelter impacts through smaller dwelling sizes, high density living and energy saving refurbishment measures. Nevertheless, policies that encourage a shift to compact urban living should also aim for de-carbonization of heating sources typical for urban context. Urban and apartment-block dwellers are found to more likely use oil and gas for heating, and less likely to use renewables and heat pumps, highlighting the need for top-down incentives for low-carbon heating in urban environment. Our analysis shows that lowering heating needs may reduce the reliance on fossil fuels, but strong incentives are needed for a transition to renewable heating sources. Prior studies have shown that district heating competes with natural gas and other fossil-based energy supply in high heat density urban area (Euroheat and Power, 2006), pointing to the de-carbonization of district heating as another priority in urban context. Furthermore, our sample suggests that household sizes tend to be smaller in urban areas (in line with Ottelin et al., 2015), suggesting the need to further enable household economies of scale in urban context. Although not investigated here, our results suggest that multi-household living could reduce shelter impacts, and options like co-housing have been proposed for their benefits (Williams, 2008). Finally, cities can be particularly vulnerable to climate change with high-density areas exposed to, for example, heat waves or coastal flooding (Dora et al., 2015).

With higher income levels, there are also expected CF increases, particularly associated with air travel and other consumption. Our findings confirm the relevance of income for mobility, food and clothing domains (Ivanova et al., 2017; Pullinger, 2012; Sommer and Kratena, 2016). A reduction in working hours without proportionate decreases in income would likely be of little relevance for emissions. Yet, longer working hours are associated with lower carbon intensity of travel, in line with the hypothesis that leisure travel is not only constrained by money but also time (Czepkiewicz et al., 2018).

Furthermore, we find the primary reasons for not heating to be financial, with higher income levels significantly reducing the likelihood of not heating. Importantly, green industrial policies may result in rising electricity prices for consumers, with the financial burden unequally distributed across social groups (Meckling et al., 2017; Wiedenhofer et al., 2013). Therefore, the transition to renewables should consider the potential for energy poverty and cold-housing related social hazards (Ürge-Vorsatz et al., 2014).

While our analysis confirms the importance of air travel in terms of climate impact (in line with Aamaas et al. (2013); Aamaas and Peters (2017)), the power of selected factors to explain observed variation in air-travelled distance is rather limited. We find that higher income and education are associated with a higher likelihood of air travel, which confirms (international) travel as highly income-elastic and carbon-intensive (Lenzen et al., 2018).

Car ownership is a significant carbon lock-in for our sample. This is in line with prior analysis pointing to conventional passenger vehicles as the highest carbon lock-in due to established subsidies, social norms, and supporting infrastructure (Seto et al., 2016). Nevertheless, there needs to be a behavioral alternative (e.g. public transport, manageable distance) for a change in car travel to occur. Directing public funds towards infrastructural development with significant social (inclusiveness, equality) and environmental (enabling active and public transport) consideration is key. Furthermore, upscaling of car- and ride-sharing initiatives may widen the choice of transport mode and enable carpooling, thus, significantly reducing mobility emissions. We also find low relevance of attitudes and use of energy initiatives for the shelter footprint, although benefits may occur beyond the domain of initiative activity.

This study points to key factors that shape energy demand and GHG emissions in high structural carbon-intensive consumption domains, which have important implications for policy design and climate mitigation. Increasing settlement density, while reducing travel distance, income, and car ownership rates, holds potential for significant emission reductions in the mobility domain. Key considerations for carbon mitigation in the shelter domain include dwelling characteristics, such as size, type, time of construction, refurbishment level, as well as income, energy use and household trends. Furthermore, we highlight the

Table 7
Summary of effects and related policy-relevant considerations.

Drivers	Effects on Mobility Footprint	Effects on Shelter Footprint	Effects on Other Consumption	Policy-relevant considerations
Mobility- and shelter-specific drivers: distance, travel characteristics, energy use and dwelling characteristics	● Longer distance reduces active travel (less so for public transport) ● Car ownership is a carbon lock-in with high likelihood of driving (even at short distances) ● No voluntary substitution between short flights and public land travel ● Work trips more likely to be done via public transport	● Higher electricity use increases the likelihood that electricity is used as a heating source Larger dwelling size more likely to be heated by renewables/ heat pump (and by district heating); larger dwelling have also higher space heating needs ● Apartments have lower energy needs and are less likely to heat by renewables and more likely to heat by district heating ● Newer dwellings/better thermal insulation associated with lower heating needs (potentially higher electricity consumption)	● Active travel associated with lower food and clothing footprint ● Air travel and car ownership associated with higher food- and clothing footprint ● Higher energy use is associated with higher food-and clothing-footprint ● Respondents living in newer dwellings associated with higher food footprint ● Own electricity production associated with lower clothing footprint	● Reduce travel distance (e.g. urban connectivity, telecommuting) ● Reduce carbon intensity of travel – encourage active/public travel (e.g., urban connectivity, infrastructure, financial incentives, bans and regulations), carpooling, tackle car ownership lock-in (e.g. incentives to change habits, parking and zoning restriction, vehicle and fuel tax), fuel decarbonization and efficiency gains ● Reduce long distance travel and intensity (e.g. infrastructure, telecommuting, efficiency improvements, capacity constraints, carbon taxes or trading schemes) ● Reduce energy use (e.g. efficiency improvements, dwelling standards, taxes) ● Reduce carbon intensity of energy (e.g. regulations, financial incentives)
Attitudes and use of initiatives (ride sharing, energy coops)	● More favorable mobility-initiative attitudes are associated with a reduction in the land-traveled intensity (lower likelihood of driving) and a rise in air-based carbon intensity ● Use of initiatives rise land-travel distance (holding car ownership constant)	● Energy-initiative attitudes insignificant for shelter impacts ● No relevance of initiative use on total energy use; users of energy cooperatives less likely to "not heat"; more likely to heat water by electricity	● More favorable attitudes associated with lower food/ clothing footprint	● Evaluate the holistic effect of initiatives (e.g. spillover effect, reduction in car ownership) ● Low relevance of domain-specific attitudes for emissions ● Account for potential rebound with use of initiatives
Urban-rural context and household size	● Urban context associated with lower travel distance by land, more active and public transport ● Limited household economies of scale (e.g. due to differences in travel routines)	● No direct effect of rural context on energy use, though important urban-rural differences in dwelling characteristics ● Household economies of scale for energy needs. No significance for carbon intensity	● No significant household economies of scale ● No relevance of urban-rural typology (keeping income constant)	● High-density infrastructural development, incentives for compact multi-household living (e.g. sprawl taxes) considering other trends (e.g. income, household size) ● Incentives for mitigating the carbon intensity of shelter particularly in urban environment
Socio-demographics	● Females travel lower distances both by land and air, and are more likely to opt for public transport ● Well-educated travel more actively on the ground and by air ● Married more likely to drive	● Limited relevance for the choice of heating source ● Married and younger associated with lower energy needs; females associated with higher space heating needs	Limited relevance: ● Females and more educated with lower food footprint	● Differences in time use and expenditure patterns of various groups should be considered (e.g. flexible working schemes, living situation) ● Raising awareness about other benefits of active travel (e.g. health)
Income and working hours	● Air travel is very income elastic (intensity, distance) ● Rising income increases land-travel distance ● Limited relevance for transport mode and car ownership (own vehicle not a luxury) ● Higher working hours may actually reduce the carbon intensity of travel	● Income and working hours are of limited relevance for shelter. ● Higher income classes are less likely to not heat	● Rising income increases footprints in both food and clothing domains with clothing being the most income-elastic	● Reduction in the average paid working time are expected to produce emission decreases in most categories. ● Schemes targeting only working hours (keeping income constant) would likely not produce significant footprint changes ● Fuel poverty needs to be addressed (especially in the case of rising energy prices) with financial saving potentially being a significant driver to not heat.

strong need to tackle car ownership, air travel and heating. Our study makes a key contribution towards the design of adequate policies to enable a successful transition to sustainability.

Acknowledgements

This work is an output of the GLAMURS project financed by the European Union's seventh framework program [contract 613420]. We would like to thank all GLAMURS partners who have contributed to the GLAMURS surveys, during the stages of design, distribution, and collection of data. The list includes but is not necessarily limited to Ricardo García-Mira, Alberto Díaz-Ayude and Helena Martínez Cabrera from UDC, Ines Omann, Mirijam Mock, Paul Lauer and Ines Thronicker from UFZ, Giuseppe Carrus, Fridanna Maricchiolo, Angelo Panno, Ambra Brizi and Eugenio de Gregorio from the Roma Tre University, Vlad Pandur from UVT, Maxie Schulte, Ellen Matthies and Anke Blöbaum from OVGU. The authors thank Angela McLean for writing assistance.

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Supplementary information:

Carbon mitigation in domains of high consumer lock-in

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Survey design

Case studies

The regional samples include Galicia (Spain), Lazio (Italy), Banat-Timis (Romania) and central Germany (Germany). A brief background on each region is provided below.

Procedures

The following section describes the process of sampling, translation of the GLAMURS survey into different languages, as well as the programming and distribution of the survey. More details are provided elsewhere[1]. GLAMURS survey contained questions on lifestyle domains, footprint-related behaviors and psychological constructs (e.g. norms, values, aspirations). The final survey was then programmed as an online questionnaire in English. Project team members from every country translated the items into their own languages. The case-study teams were strongly advised to implement a back-translation process to ensure that the items kept their meaning in the country-specific language. A thorough online survey in the specific country's language was prepared and coded, which was hosted by the SoSci software.

A pilot study was conducted in two of the regions – Galicia (ES) and Saxony-Anhalt (DE) – to test the comprehension of the survey and the validity of the measures. The pilot samples included 94 and 50 respondents respectively. The final survey was adapted based on the insights from the pilot (see Dumitru et al. (2016) for more detailed description of the procedure and results).

The link to the survey was distributed in different ways between the months of December 2015 and February 2016, e.g. using mailing lists or by contracting a company ensuring a representative sample from the region. Data was collected as a single dataset enable direct inter-regional comparisons. The samples were recruited in a multi-stage process with a phase of contacting participants via a snowball-system adopted across all case studies. Detailed official statistics and discussion on representativeness have been provided by Dumitru, Diaz, et al. (2016).

Sample representativeness

Below we compare with regional official statistical data to report the extent to which the sample differed from the regional distribution of the population. However, it should be mentioned that exploration of relationships between different dimensions was more important in the analysis of GLAMURS survey, given that research design touches on areas that have been explored in a very limited manner before, and thus regional representativeness was less essential. We exclude the initiative sample in the comparison below.

Spanish case study – the region of Galicia

More detailed official stati1stics have been provided by Dumitru, Diaz, et al. (2016). Based on the comparison with regional statistics, our sample appears somewhat younger, more female-represented and more educated. According to our analysis, females, younger and more educated people are associated with lower food-, housing- and transport-footprints (except for the age effect on transport emissions and education effect on food emissions).

	Our sample	Official statistics
Age	35	45
Gender	30 % men 70 % women	49 % men 51 % women (2015 data)
Income	Annual household net income range Median: 18,000-36,000 EUR Mean: 18,000-36,000 EUR	Average annual household income 22,980 EUR (2014 data)

SI Table 1: Comparison between our regional sample and official regional statistics: Galicia (Spain)

Italian case study – the region of Lazio

Official regional statistics for Lazio have been collected from *Istat.it.* Our sample appears to be slightly younger with an overrepresentation of females. According to our analysis, females and younger people are associated with lower food-, housing- and transport-footprints (the only exception being the age impact on transport emissions). Therefore, if anything we are understating the region's consumption-based emissions making it more difficult to conclude a significant initiative effect. Our sample matches the regional statistics in terms of education and income.

	Our sample	Official statistics	Year
Age	40	44.3	2016
Gender	40 % men 60 % women	48.2 % men 51.8 % women	2016
Income	Annual household net income range Median: 18,000-36,000 EUR Mean: 18,000-36,000 EUR	Annual household income Median: 23,866 EUR Mean: 28,991 EUR	2014

SI Table 2: Comparison between our regional sample and official regional statistics: Lazio (Italy)

German case study – the region of Central Germany

The USUMA GmbH, Berlin, Germany, was appointed to recruit a stratified sample showing the representative characteristics of the region Saxony-Anhalt. This way, a representative sample for the German case study was achieved. USUMA recruited 800 people via telephone interviews, weighing that sample for the criteria of age, household sizes, income, educational level etc. The sample was then presented with the online survey. The match between regional statistics and sample characteristics was achieved.

	Our sample
Age	53
Gender	45 % men 55 % women
Income	Annual household net income range Median: 18,000-36,000 EUR Mean: 18,000-36,000 EUR

SI Table 3: Comparison between our regional sample and official regional statistics: Saxony-Anhalt (Germany)

Romanian case study – the region of Banat-Timis County

The latest official data from 2011 has been used to discuss representativeness of our sample [4]. Instead of income, the annual value of expenditure and other money outputs for the West region in per household is reported (for more details see Family Budgets Survey, NIS).

	Our sample	Official statistics
Age	32	Included in the most numerous age interval for regional population (20 – 40 years old)
Gender	40 % men 60 % women	47.2 % men 52.8 % women
Income	Annual household net income range Median: 3,972 – 6,612 EUR Mean: 6,613 – 10,584 EUR	28,692 lei (6,000 EUR average)

SI Table 4: Comparison between our regional sample and official regional statistics: Banat-Timis (Romania)

GLAMURS Questionnaire

Category	Survey question	Answer values	Used for FP calculations	Used as regressor
Regular commute	Thinking about your commute between work and home during a regular week, could you please indicate the means of transport you use, the number of return trips you make on average, and the approximate distance covered in km? Where in doubt, please answer approximately and as closely to your reality.	Table including modes: walking, bicycle, electric bicycle, motorbike, car, bus, tram/underground, commuter train	Yes	Yes
Private trips	Thinking about your regular private trips during a regular week, could you please indicate the means of transport you use, the number of return trips you make on average, and the approximate distance covered in km? Where in doubt, please answer approximately and as closely to your reality.	Table including modes: walking, bicycle, electric bicycle, motorbike, car, bus, tram/underground, commuter train	Yes	Yes
Car ownership	Which of the following options best describes your situation?	(1) I own a car and I am the only one who uses it., (2) I share the car with other members of my household, (3) When I need a car, I use a carpooling service.	Yes	Yes
Car characteristics	[Only for options 1 and 2 of MB3] Please, indicate the type of car you have or share with members of your household, and the fuel it uses:	(1)Mini, (2) Compact, (3) Large/familiar/station wagon, (4)SUV/4x4	Yes	
Fuel characteristics	[Only for options 1 and 2 of MB3] Please, indicate the fuel it uses:	(1)Gasoline, (2)Diesel, (3)Gas (GPL/Methane),(4)Hybrid, (5)Electrical	Yes	
Fuel use	How much fuel does your car use per 100 km?	Open question	Yes	
Top-down car distance	How many km do you drive per year with your car, approximately (please refer only to the km you drove)?	(1) Less than 5000 km, (2) Between 5000 and 10000 km, (3)Between 10000 and 15000 km, (4) Between 15000 and 20000 km, (5) Between 20000 and 40000 km, (6) Between 40000 and 60000 km, (7)Over 60000 km	Yes	
Carpooling to work	When you travel, how often do you carpool rather than drive alone, in the following situations? for work	(1) means Never, (7) means Always	Yes	
Carpooling to private	When you travel, how often do you carpool rather than drive alone, in the following situations? for private	(1) means Never, (7) means Always	Yes	
Air travel	How many return flights did you take for private trips in total in the last year (2014)?	Open question	Yes	
Air travel	How many of the return flights were short/long? Short (Less than 4.000 km or less than 4 ½ hours), Long (more than 4.000 km or 4 ½ hours)	Open question	Yes	
Dwelling size	What is the size of your current residence?	Open question in square meters or rooms	Yes	Yes

Dwelling type	Please indicate the type of dwelling	(1) Single family house, (2) terraced house (identical houses in a row), (3) Multi-family house (less than 10 families in one complex), (4) Apartment block (more than 10 dwellings)	Yes	Yes
Year of construction	How old is the building in which your home is located?	Please indicate year of construction; for those answering "I don't know": (1) built before 2000, built after 2000	Yes	Yes
Electricity bill	How much do you pay per month on electricity, on average in your household, during the following seasons? Winter/summer	Open question	Yes	
Heating home	How do you primarily heat your home?	(1) Oil (radiators), (2) Gas (natural gas, central heating oil, propane), (3) pellets/firewood, (4) Solar-thermal heater, (5) Electric/gas heat pump, (6) District heating, (7) Electricity (underfloor, heating, accumulators, convectors), (8) I do not heat my home	Yes	
Heating water	How do you primarily heat water in your home?	1) Oil, (2) Gas (natural gas, central heating oil, propane), (3) pellets/firewood, (4) Solar-thermal heater, (5) Electric/gas hot water tank, (6) District heating, (7) Electricity (water heater), (8) I do not heat water in my home	Yes	
Electricity production	Do you produce any electricity yourself?	Yes/no, % of produced electricity		Yes
Temperature settings	During the cold season, how often do you turn on the heating system, during an average week?	(1) Never, (2) Only cold days, (3) Every day when staying at home, (4) It is always on	Yes	
Temperature settings	During cold season, how do you usually heat your home? 1	(1) The whole home, (2) Only the used rooms		
Temperature settings	How warm do you keep your house in winter on average, when you are at home? Please, choose the average temperature from the following options	(1) I never heat my house, (2) 16 degrees, (3) 17 degrees, …, (9)23 degrees, (10) 24 degrees, (11) More than 24 degrees	Yes	
Thermal insulation	Thinking about the quality of the thermal insulation of your home, would you say it is ...	(1) means Very bad, (7) means Very good	Yes	
Food spending	Of the budget you spend on food during a week, please indicate how much you spend on food purchases in stores (supermarket, local market, neighborhood stores etc.). Please, answer thinking only your own expense (if you know the total cost of your home, please divide the total by the number of people living in your home).	Open question	Yes	
Food consumption	How often do you consume the following products on average? Beef, pork, chicken, dairy products, pre-prepared food, vegetables and fruits, drinks.	(1) Never, (2) 1 day a week, (3) 2 days a week, (4) 3 days a week, (5) 4 days a week, (6) 5 days a week, (7) 6-7 days a week	Yes	
Food consumption	Would you indicate your weight?	Open question (in kg)	Yes	
Clothing spending	What is the total sum that you spent on clothing, shoes and/or accessories during the last three months, on things you bought for yourself?	Open question	Yes	
Second-hand consumption	How often do you purchase clothes from second-hand shops?	(1) means Never, (7) means Always	Yes	
Attitudes towards sustainability initiatives	Here is a list of initiatives that have been started in recent years. Please indicate your opinion about them: Ride sharing, car sharing initiatives/platforms (e.g. Blablacar, Amovens, Carpooling, etc.)	(1) means Very negative, (7) means Very positive		Yes
Attitudes towards sustainability initiatives	Here is a list of initiatives that have been started in recent years. Please indicate your opinion about them: Energy cooperatives (e.g. Som Energia, etc.)	(1) means Very negative, (7) means Very positive		Yes
Use of sustainability initiatives	Now please indicate how often you make use of their services (e.g. Blablacar, Amovens, Carpooling, etc.)	(1) means Never, (7) means Always		Yes
Use of sustainability initiatives	Now please indicate how often you make use of their services (e.g. Som Energia, etc.)	(1) means Never, (7) means Always		Yes
Gender	What is your gender?	(1) Male, (2) Female		Yes
Age	What is your age?	Open question		Yes
Education	What is your highest level of education?	(1) No education, (2) Primary school, (3) Secondary school, (4) High school, (5) Vocational school, (6) College degree, (7) Master degree, (8) Doctorate level		Yes
Relationship status	What is your marital status?	(1) Single living alone, (2) Single living with others, (3) Married/in a stable relationship, (4) Divorced/separated, (5) Widow/widower		Yes
Household size	Please indicate the total number of people living in your household (including those under 18 and including yourself)	Open question		Yes
Income	Monthly Net Income in your household (total monthly amount for all members of your household after deduction of all taxes)	(1) < 600€, (2) 601-1500€, (3) 1501-3000€, (4) 3001-4500€, (5) 4501-6000 €, (6) >6000€. RO sample: (1) < 176€, (2) 177-330€, (3) 331-552€, (4) 553-882€, (5) 883-1214€, (6) >1214€.		Yes
Urban-rural	How would you describe your living area?	(1) Urban, (2) Suburban, (3) Rural		Yes
Work time	How many hours do you work per week on paid work, including overtime	Open question		Yes

SI Table 5: GLAMURS questionnaire collecting attitudinal, behavioral and contextual data used for footprint calculations and determinants analysis.

Carbon footprint calculations

Food and clothing

A detailed account of the food and clothing footprint calculations is provided by [5]. Regarding the food domain, the EFSA Comprehensive European Food Consumption database was used to get information about an average adult's daily intake (e.g. for meat, dairy products, vegetables and fruits consumption) per kg of body mass across countries [6]. This was used in combination with respondents' weight to calculate adequate daily intake across food items. In addition, LCA studies were used to provide information about the carbon intensity of food items, with results standardized in $kgCO_2eq/kg$ edible product. EXIOBASE carbon intensities per EUR and prices (BPs) were used where product expenditure information was available.

We utilized expenditure multipliers from the regionalized CES-MRIO analysis (based on consumer expenditure surveys and EXIOBASE) to produce clothing-based footprints [7]. The following intensities are applied in $kgCO_2eq/EUR$: 0.323 $kgCO_2eq/EUR$ in Galicia (ES), 0.648 $kgCO_2eq/EUR$ in Banat-Timis (RO), 0.491 $kgCO_2eq/EUR$ in Lazio (IT), and 0.597 $kgCO_2eq/EUR$ in Saxony-Anhalt (DE). Furthermore, respondents have been asked about their share of second-hand clothing purchases which was then discounted, thus, assigning all clothing impacts to the consumer who purchasing the clothing new.

Shelter

Electricity was inquired as the latest approximate winter and summer monthly bills and extrapolated to the annual cold and warm seasons, respectively. The yearly electricity bill was converted into kilowatt-hours by using average country prices [8]. The climate impact of electricity was calculated using country-level carbon intensities from Eco-Invent 2.2 [9]. We discounted any space and water heating delivered by electricity to avoid double-counting.

We did not ask respondents directly about their energy use for space and water heating as we considered it difficult to accurately estimate for an average consumer. Therefore, rather than enquiring about it directly, we collected dwelling-specific data based on which we calculated typical energy demand. The impact of space heating depends on the interaction of a set of factors. These include, choice of heating fuels, building characteristics, electricity mix in the region, occupancy, energy needs and living space.

The methodology and metadata used for the physical energy demand has been developed in the course of the Intelligent Energy Europe project TABULA [10]. It was primarily designed to collect and compare data of example buildings representative of the national building stock in Europe. The physical concept behind the footprint of space heating is based on estimating the typical energy demand given the (1) type of house, (2) year of construction, (3) the level of refurbishment and the (4) climate zone of the region (R squared = 0.48). Regression coefficients have been estimated based on the pooled European sample for the four types of dwellings, 6 construction periods, 3 levels of refurbishment and 8 climatic zones (SI table 6).

$$Yearly\ Space\ Heat\ Demand\ \left(\frac{kWh}{m^2 - annum}\right) = \beta_0 + \beta_1(Climate_i) + \beta_2(Construction\ Period_i) + \beta_3(House\ Type_i) + \beta_4(Refurbishment_i) + \epsilon_i$$

Product and unit	Intensity used	Consumption
Electricity	0.5184 (Galicia, ES), 0.7452 (Banat-Timis, RO), 0.6569 (Lazio, IT), 0.6586 (Saxony-Anhalt, DE). National electricity mix[9] ($kgCO_2eq/kWh$)	Electricity spending from the survey
Space and water heating	0.33 (Oil), 0.277 (Gas), 0.04 (Firewood Pellets)[11], 0.001 (Solar Thermal Heater), 0.038 (Electric/gas heat pump), 0.42 (District Heating)[9]. European average to prevent noise from country-specific factors. Also see "Electricity" intensities for heating by electricity. From primary to delivered energy. ($kgCO_2eq/kWh$)	Space heating needs calculated using TABULA and data on dwelling type and size, refurbishment level, climate zone, construction period and household size (Adjusted R-squared: 0.47, Obs. 1412)
Water heating	0.33 (Oil), 0.277 (Gas), 0.04 (Wood Pellets)[11], 0.001 (Solar Thermal Heater), 0.038 (Electric/gas hot water tank), 0.42 (District Heating)[9]. European average to prevent noise from country-specific factors. Also see "Electricity" intensities for water heating by electricity. ($kgCO_2eq/kWh$)	Water heating needs calculated using TABULA

SI Table 6: Summary of shelter-related emission intensities and consumption.

The total theoretical energy demand per square meter was scaled to the living space areas and divided by the number of inhabitants in the household. A default 20°C indoor temperature was assumed for heating calculations. The hot water demand was calculated using a model in function of occupants [12].

Carbon intensity of energy carriers for space and water heating was based on the Tabula[10]. The heating fuels and technologies employed by the household for space and water heating were considered measuring their carbon intensity emissions factors (in kgCO_2e/kWh) from Eco-Invent.

Transport

We collected data on transport means and distance of regular return trips, including active transport (walk, bicycle, e-bicycle), private motorized transport (car, motorbike) and public transport (bus, tram/underground, train). We refer to these as "bottom-up" transport calculations, as the annual travel distance (in km) and footprints was scaled up to a yearly calculation from weekly reports on individual trips. Respondents were given the option to fill out information for more than one regular trip.

With regards to land travel, we considered embodied life cycle carbon emissions, and direct tailpipe emissions associated with the vehicle's use. Physical carbon intensities were calculated based on LCA studies and Eco-invent 2.2. Most studies capture emissions from cradle-to-grave considering the product and service fluids (see SI table 12). The following carbon intensities in kgCO_2eq/pkm were applied (disregarding emissions from production of food to meet energy needs associated with active travel): walking (0), bicycle (0.005), electric bicycle (0.018), motorbike (0.120), average car (0.198), and bus (0.132).

Furthermore, private car users provided information on car ownership and shared usage, car and fuel type and age of the car, which were used to develop car- and fuel-specific carbon emission factors. In the cases of carpooling, both direct and indirect emissions were split between the users. We assumed that carpooling is done with at least one more person, which could potentially over-state car travel emissions in cases where car-pooling is done with more than two passengers.

The regular car travel distance was validated with the annual "top-down" estimate that car users provided – ideally from their odometer. The following range was provided: 1 (Less than 5,000 km), 2 (Between 5,000 and 10,000 km), 3 (Between 10,000 and 15,000 km), 4 (Between 15,000 and 20,000 km), 5 (Between 20,000 and 40,000 km), 6 (Between 40,000 and 60,000 km), 7 (Over 60,000 km). We assumed a top-down upper limit of 80,000 km for "over 60,000" values. For the cases where the bottom-up travel estimate was below the top-down estimate, we prioritized the top-down measure. We applied the same upper limit of 80,000 km/year (or 220 km/day) across all transport modes.

In terms of fuel, direct and indirect emissions were calculated based on the GWP100 potential from Ecoinvent. European average to prevent noise from country-specific factors (except electricity). The following values were utilized: petrol (2.957 kgCO_2eq/L), diesel (3.108 kgCO_2eq/L), hybrid petrol (2.957 kgCO_2eq/L), electricity (0.455 kgCO_2eq/kWh), LPG (2.361 kgCO_2eq/L). The specific region's carbon intensity was adopted. The car production emissions data is collected from LCA studies (EOL GWP100) and is measured in kgCO_2eq/km, here again reported by type of fuel: petrol (0.062 kgCO_2eq/km), diesel (0.057 kgCO_2eq/km), gas (0.062 kgCO_2eq/km), electricity (0.051 kgCO_2eq/km) and hybrid (0.048 kgCO_2eq/km). Finally, a car's fuel consumption measured in L/km or kWh/km is dependent on the type of fuel and car:

Type of car	City car	Compact	Family car	Large car
Petrol (in L/km)	0.058	0.058	0.074	0.099
Diesel (in L/km)	0.048	0.048	0.058	0.082
Hybrid (petrol-electric) (in L/km)	0.029	0.029	0.041	0.058
Electricity (in kWh/km)	0.125	0.125	0.147	0.188
LPG (in L/km)	0.095	0.095	0.131	0.136

SI Table 7: Fuel efficiencies by type of car and fuel.

We calculated emissions associated with tram and train travel differently, as direct emissions associated with these transport modes varied with the carbon intensity of the local electricity mix (see SI table 8). We calculated the transport footprint associated with traveling by tram or underground using 0.13 kWh/pkm, applying the carbon intensity of the electricity mix from Eco-Invent. Indirect emissions amount to 0.015 kgCO_2eq/pkm. Following the same procedure, we calculated the transport footprint associated with traveling by tram or underground using 0.08 kWh/pkm. The indirect emissions amount to 0.019 kgCO_2eq/pkm.

Case Study Region	Carbon intensity of the electricity mix (kgCO_2eq/kWh)	Carbon intensity of tram travel (kgCO_2eq/pkm)	Carbon intensity of train travel (kgCO_2eq/pkm)
Galicia	0.518	0.015 + 0.068	0.019 + 0.041
Banat-Timis	0.745	0.015 + 0.098	0.019 + 0.060
Lazio	0.657	0.015 + 0.087	0.019 + 0.053
Saxony-Anhalt	0.659	0.015 + 0.087	0.019 + 0.053

SI Table 8: Carbon intensities per pkm for tram/underground and train

Air travel was based on the annual number of short- and long-haul flights. We treated as outliers observations with a number of return flights above 365 in a year. We allocated emission factors for air depending on flight length[13], which included radiative forcing index (RFI) of 1.9 (except for domestic flights) (see SI table 12). The RFI compares the total radiative forcing effect caused by aviation to that caused by CO_2 alone[13]:

$$RFI = \frac{RF(CO_2) + RF(O_3) + RF(CH_4) + RF(H_2O) + RF(contrails) + RF(particles)}{RF(CO_2)}$$

With regards to short-haul flights, we collected information about national and international air passenger transport in 2015, focusing on the four countries of our sample[14,15]. Short-haul flights were described in our questionnaire as return flights below 4000 km. Therefore, in our analysis of frequent air travel and destinations we focused on within-EU flight distributions. The four countries represented 41% of total EU passenger air traffic, including both national and international air travel.

	Germany			Spain			Italy			Romania		
	Int Share	Berlin or Frankfurt		Int Share	A Coruna or Madrid		Int Share	Rome		Int Share	Timisoara or Bucharest	
Belgium	0.02	Brussels	1 268	0.05	Brussels	2 544	0.05	Brussels	2 348	0.05	Brussels	2 706
Bulgaria	0.01	Sofia	2 664	0.00	Sofia	4 498	0.01	Sofia	1 848	0.01	Sofia	602
Czech Republic	0.01	Prague	564	0.01	Prague	3 502	0.01	Prague	1 872	0.01	Prague	2 166
Denmark	0.03	Copenhagen	684	0.02	Copenhagen	4 118	0.02	Copenhagen	3 074	0.00	Copenhagen	3 108
Germany				0.21	Frankfurt	2 840	0.17	Frankfurt	1 918	0.18	Frankfurt	2 124
Estonia	0.00	Tallinn	2 090	0.00	Riga*	5 388	0.00	Riga*	3 758	-	Tallinn**	3 536
Ireland	0.02	Dublin	2 620	0.03	Dublin	2 906	0.02	Dublin	3 776	0.01	Dublin	5 068
Greece	0.05	Athens	3 650	0.00	Athens	4 760	0.04	Athens	2 174	0.03	Athens	1 520
Spain	0.24	Madrid	3 708				0.16	Madrid	2 664	0.11	Madrid	4 196
France	0.07	Paris	1 758	0.09	Paris	2 058	0.14	Paris	2 180	0.07	Paris	2 988
Croatia	0.01	Zagreb	1 570	0.00	Zagreb	3 388	0.00	Split	766	0.00	Zagreb	1 596
Italy	0.12	Rome	2 400	0.10	Rome	2 664				0.24	Rome	1 664
Cyprus	0.00	Pafos	5 002	0.00	Larnaca	6 620	0.00	Larnaca	4 024	0.01	Larnaca	2 512
Latvia	0.01	Riga	1 678	0.00	Riga	5 388	0.00	Riga	3 758	0.00	Riga**	2 980
Lithuania	0.00	Vilnius	1 650	0.00	Vilnius	5 296	0.00	Vilnius	3 438	0.00	Vilnius**	2 646
Luxembourg	0.00	Luxembourg	1 186	0.00	Luxembourg	2 544	0.00	Luxembourg	1 976	0.00	Brussels*	2 706
Hungary	0.01	Budapest	1 424	0.00	Budapest	3 952	0.01	Budapest	1 674	0.01	Budapest	482
Malta	0.01	Luqa	3 296	0.00	Luqa	3 316	0.01	Luqa	1 380	0.00	Luqa	2 764
Netherlands	0.04	Amsterdam	1 152	0.05	Amsterdam	2 920	0.06	Amsterdam	2 596	0.05	Amsterdam	3 572
Austria	0.07	Vienna	1 278	0.01	Vienna	3 614	0.02	Vienna	1 560	0.04	Vienna	1 662
Poland	0.04	Warsaw	1 048	0.01	Warsaw	4 544	0.02	Warsaw	2 656	0.01	Warsaw	1 852
Portugal	0.04	Lisbon	4 610	0.03	Lisbon	1 014	0.02	Lisbon	3 684	0.01	Lisbon	5 952
Romania	0.02	Bucharest	2 124	0.01	Bucharest	4 924	0.03	Bucharest	2 328			
Slovenia	0.00	Ljubljana	1 220	0.00	Zagreb*	3 388	0.00	Trieste	916	0.00	Ljubljana	1 856
Slovakia	0.00	Vienna*	1 246	0.00	Bratislava	3 708	0.00	Vienna*	1 560	0.00	Vienna*	1 662
Finland	0.02	Helsinki	2 240	0.01	Helsinki	5 898	0.01	Helsinki	4 470	0.00	Helsinki	3 508
Sweden	0.03	Stockholm	1 680	0.03	Stockholm	5 204	0.01	Stockholm	4 050	0.01	Stockholm	3 402
United Kingdom	0.13	London	1 896	0.31	London	2 174	0.17	London	2 892	0.15	London	3 438

SI Table 9: Intra-EU traffic at country levels. The return distances were calculated using FlightRadar24. Market destinations had no direct connections, so distances were calculated to the closest international destination (*) or with 1 stop (**). Source: Eurostat and FlightRadar[14,16]

SI table 9 depicts the intra-EU traffic for the four countries in our sample. The first column on the left includes partnering countries. See Eurostat[14] for a full account of passenger numbers by country pairs. The following airports were considered: Berlin (TXL) or Frankfurt (FRA) for Germany, A Coruna (LCG) or Madrid (MAD) for Spain, Rome (FCO) for Italy, and Timisoara (TSR) or Bucharest (OTP) for Romania.

The primary option (local airports) was used as a first choice to calculate flight distances where destinations to the partner country were available (e.g. A Coruna for ES). In the cases of no direct connections, we considered larger airports for our sample countries (e.g. Madrid for ES).

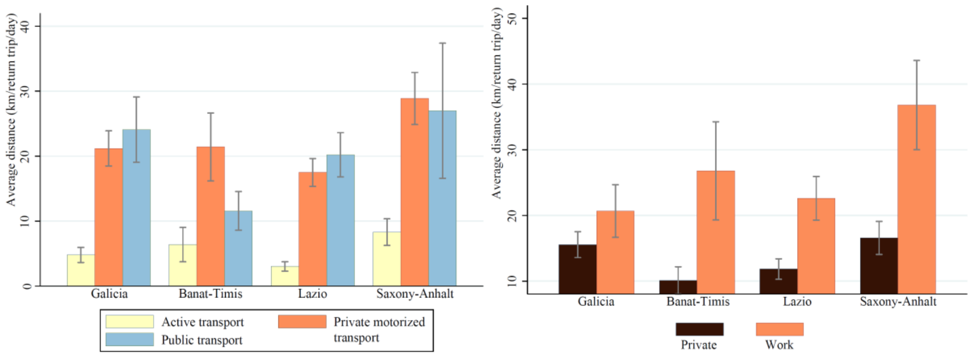
Then, for each of the four countries in our sample we present the international share of travel by country pair, the most typical destinations for each country pair, and the distance of a return flight between them. The international shares add up to 1 for each sampled country and are informed by air travel passenger statistics from Eurostat[14]. Then, we explored FlightRadar to get an idea about typical travel routes and distances[16]. We could then calculate the average distance for an international return trip across the four counties – 2443 km (82% of air travel) for Germany, 2695 km (79%) for Spain, 2467 (71%) for Italy, and 2612 km (95%) for Romania (SI table 10). The overwhelming majority of passengers in the EU take international flights[14,15].
The share of domestic flights values between 5-29% for the countries in our sample (SI table 10). Again, using FlightRadar we considered the most frequent domestic destinations (in top 10 for each local airport) and their return distances. Finally, we could calculate the average short return trip across countries, varying between 2041 for Italy and 2529 for Romania. Finally, we adopted average return trip distance of 2300 km for the whole sample, considering our sample distribution. Assuming the same distance for each country, we could estimate footprint difference, only due to differences in behavior (number of flights).

	Share	Average return trip	Share	Average return trip	Share	Average return trip	Share	Average return trip
International	0.82	2 443.20	0.79	2 695.47	0.71	2 467.40	0.95	2 612.29
Domestic	0.18	938.98	0.21	1 297.49	0.29	985.12	0.05	813.83
Average return trip		2168		2402		2041		2529

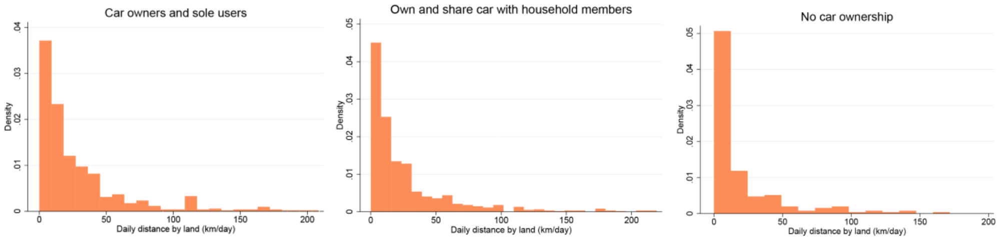
SI Table 10: Average short return trip by country. Source: Eurostat and FlightRadar[14–16]

With regards to long-haul destinations, the range is much larger. For example, DEFRA reports long-haul destinations between 3300 and 17000 one-way[17]. On average CAA statistics[17] report a return long-haul distance of 10000 km. In order to not overstate the importance of long-haul travel for the average respondent (only 17% fly to long-haul destinations, and only 5% noted a number of return flights >2) we assumed a return trip distance of 8000 km for long-haul flight, which is a rather conservative estimate. We discuss footprint uncertainty with regards to these assumptions in the next section.

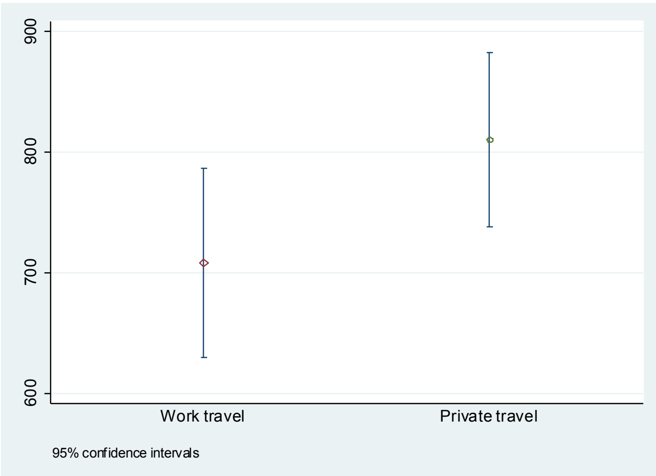
Descriptive statistics



SI Figure 1: Average return trip distance by geographic region, and (a) transport mode or (b) purpose of trip. Calculations are performed on a trip rather than individual level. 95% confidence intervals included.



SI Figure 2: Distribution of daily land travel (in km/day) by car ownership with those who car owners and sole users (left), those who own a car and share it with household members (middle) and those who do not own a car (right)



SI Figure 3: Average land-based travel footprint by work and private travel incl. 95% confidence intervals.

Transport mode	Purpose of travel	Mean of annual number of trips	Standard deviation of annual number of trips
Walk	Work	34.83	122.83
Walk	Private	18.96	29.99
Bike	Work	29.00	360.49
Bike	Private	12.01	36.91
E-bike	Work	1.28	18.01
E-bike	Private	1.14	14.27
Motor	Work	7.09	57.13
Motor	Private	6.45	37.28
Car	Work	131.24	674.95
Car	Private	190.57	196.03
Bus	Work	18.03	81.41
Bus	Private	43.29	109.66
Tram/underground	Work	11.68	64.01
Tram/underground	Private	25.57	93.63
Train	Work	5.66	34.54
Train	Private	21.15	74.69

SI Table 11: Distribution of annual number of trips by transport modes and purpose of travel.

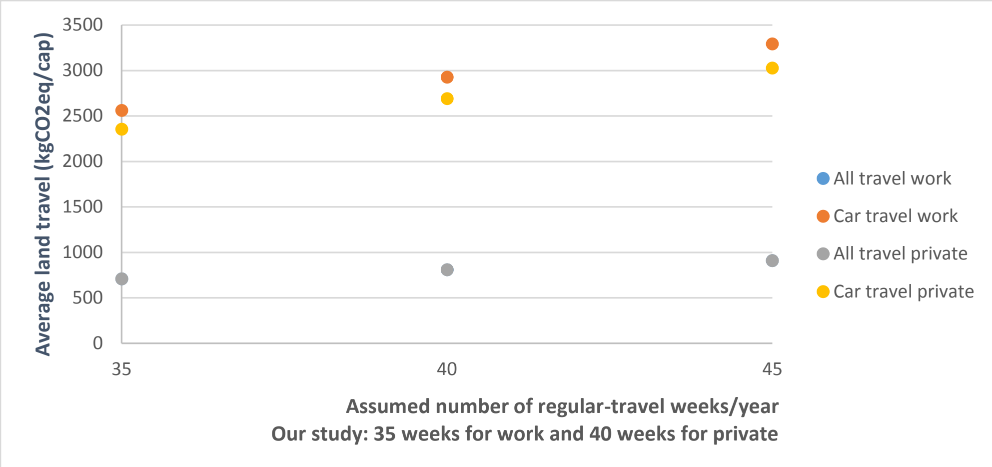
Footprint uncertainty and validation

SI table 12 provides a summary of the assumptions behind the mobility footprint calculations and we compare to other assessments and uncertainty estimates. For a full account of climate impact per passenger-km of different vehicles for various GWP and GTP metrics, including uncertainties, see Borken-Kleefeld and colleagues (2013)[18].

Product and unit	Intensity used	Sources on intensities	Consumption	Sources on consumption
Active travel	0 (Walking), 0.005(Cycling), 0.018 (e-Cycling) (kgCO_2eq/pkm)	[19]	Data collected on work and private regular trips and distance per return trip. Annual travel assumes 35 and 40 weeks/year for work and private purpose travel, respectively.	Significant underreporting of travel, e.g. 10-15% and up to 50% for certain types of trips[20]. Off-peak and non-work purpose trips associated with higher uncertainty[20,21]. Average day-to-day variability of travel is 60%, between 47% for work and 76% for leisure[21]. German travel survey[22] (public transport): 2912 km/cap on average; Our study: 1488 (95% CI: 814-2161)
Public travel	0.132 (Diesel Bus), Production and end of life emissions: 0.015 (Tram/metro), 0.019 (regional train). National electricity mix used to power rail transports (SI table 8) (kgCO_2eq/pkm). Average passenger occupancy assumed: 15 passengers.	**Bus** (diesel): 0.132±0.023[23–31], 0.108 (only direct)[17]; Average passenger occupancy for local bus (10.8) and for coach (16.2)[17]; **Tram/metro**: 0.06±0.06 [27,32–37], 0.05-0.10 (only direct)[17]; **Train:** Long-distance/commuter rail: 0.09±0.15 [27,34,38–40]. Occupancy 30-50%; high-speed train: 0.06±0.04 [27,41,42]. Occupancy 40-70%[18] (kgCO_2eq/pkm).		
Motorbike	0.120 (kgCO_2eq/km)	0.21±0.16 [19,27,43] By CC range: direct 0.08-0.16[17]		
Car travel	**Generic car**:0.198, assuming internal combustion 4 cylinder gasoline car[44] (kgCO_2eq/pkm) **Petrol**: Fuel Production: 0.572, Direct combustion: 2.384 (kgCO_2eq/L). Fuel efficiency varying between 0.058 and 0.099 L/km from city car to large car. **Diesel**: Fuel Production: 0.468. Direct combustion: 2.640 (kgCO_2eq/L). Fuel efficiency varying between 0.048 and 0.082 L/km from city car to large car. **Hybrid** (petrol-electric): Fuel Production: 0.572; Direct combustion: 2.384 (kgCO_2eq/L). Fuel efficiency varying between 0.029 and 0.058 L/km from city car to large car. **Electric**: Fuel Production: National electricity mix (Electric). Direct combustion:0 (kgCO_2eq/kWh). Fuel efficiency varying between 0.125 and 0.188 kWh/km from city car to large car. **LPG**: Fuel production: 0.868, Direct combustion: 1.493 (kgCO_2eq/L). Fuel efficiency varying between 0.095 and 0.136 kWh/pkm from city car to large car.	**Petrol**: 0.24±0.08[43–77]; **Diesel**: 0.23±0.15 [43–46,48,51–53,55,57–60,64,69–71,73,78–80]; **Hybrid:** 0.20±0.04 [47,50,53,59,63,65,66,73,74,80–82]; **Electric**: 0.15±0.07 [50,51,53,54,58–60,62–65,69–74,79,83–86]; **LPG**: 0.21±0.05 [53,73] (kgCO_2eq/km) By cars by size: Petrol: 0.14-0.27[17,18], **Diesel**: 0.10-0.20[17,18] (assuming 35-40% average occupancy[18]) (kgCO_2eq/pkm) Occupancy: For medium and big cars: 25% - 45%; For small cars and SUV/van: 30-50%.	Data collected on work and private regular car trips and distance per return trip. Annual travel assumes 35 and 40 weeks/year for work and private purpose travel, respectively Additional considerations of carpooling and top-down annual car travel distance range.	See underreporting ranges above. German travel survey[22]: 13216 km/cap on average; Our study: 7951 (95% CI: 6850-9053)
Short flights (air travel)	0.305 (kgCO_2eq/pkm). Average for domestic, short and medium. Radiative forcing index of 1.9 used for all flights but domestic ones [13].	Mean and standard deviations .26±0.06 for domestic, 0.36±0.05 for short-haul and 0.20±0.03 for medium-haul domestic [13]. Occupancy on European destinations: 60-80%[18] At 100% occupancy, the specific climate impact is between 0.160 and 0.215 with uncertainty ranging from 0.08 to 0.330[18]	Return distance: 2300km; 0.7 tCO_2eq/ return passenger flight	Ranges[13]: return domestic (<800km), short (<2000km) and medium (<7400km);
Long flights (air travel)	0. 25057 (kgCO_2eq/pkm)	0.23±0.04 Differences by class: 0.17-0.67 [13] Occupancy: 50-80%[18]	Return distance: 8000km; 2.0 tCO_2eq/return passenger flight	Ranges[13]: 7400km< return long <28,000)

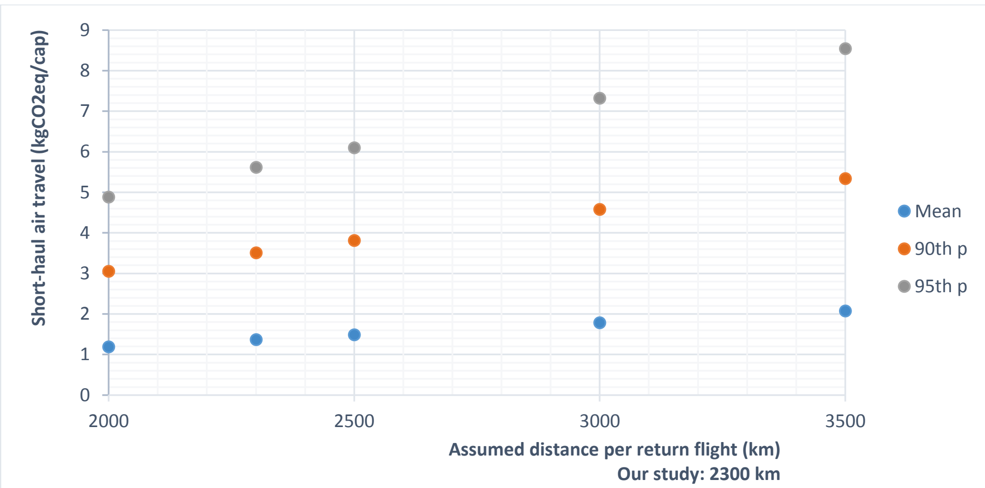
SI Table 12: Summary of mobility-specific emission intensities and consumption. All of them converted using the GWP100 metric (IPCC 2007). The method used is LCA (Life Cycle Assessment). The units for carbon intensities and consumption between our study and prior assessments are the same, unless otherwise specified. All mobility values are provided per passenger km. The ± structure depicts the mean ± standard deviation.

SI figure 3 depicts the work and private travel footprint by land separately reporting 95% confidence intervals. Particularly, work travel is estimated at 0.7 tCO_2eq/cap on average (assuming 35 travel weeks/year), compared to an average of 0.8 tCO_2eq/cap for private purposes (assuming 40 travel weeks/year). As studies suggest the larger uncertainty and underreporting associated with non-work travel, there is a potential to overstate the importance of regular work commute for the carbon footprint. SI figure 4 depicts the average land-based travel footprint for private purpose varying between 0.7 and 0.9 tCO_2eq/cap-y for a number of regular-week travel between 35 and 45. Focusing on private car travel, the average footprint varies between 2.4 and 3.0 tCO_2eq/cap-y, respectively.



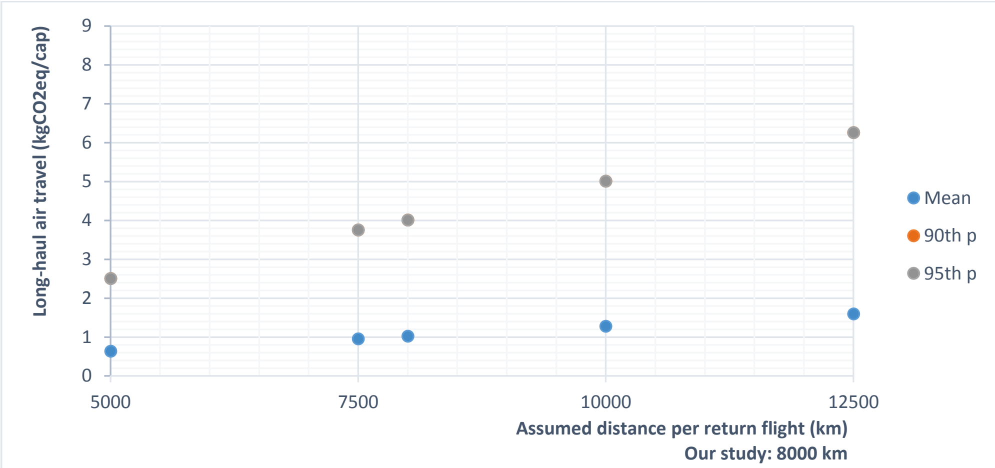
SI Figure 4: Footprint ranges by regular-travel weeks/year assumption. Average work and private footprint per week is very similar, hence, «All travel work» does not appear on the figure.

Our flight classifications in the survey only distinguishes between short (<4000 km) and long (>4000 km) return flights, so choosing a single value may be critical for the footprint comparison with other consumption domains and assessments. SI figure 5 compares footprint calculations by varying assumptions about short-haul return flight distance. As 53% of our sample do not fly to short-haul destinations, the median number of flights is 0. The blue dots on SI figure 1 depict the footprint variation assuming the mean number of flights for the sample (1.95), between 1.2 and 2.1 tCO2eq/cap for 2000 and 3500 km/return flight, respectively. For a respondent that takes 5 short-haul return flights per year (90^{th} p), the footprint variation is between 3.0 and 5.3 tCO2eq/cap, respectively.



SI Figure 5: Footprint ranges by various short-haul distance assumptions.

Even larger are the proposed distance ranges for long-haul destinations. For example, long-haul return flights from the UK may range from 6000 to 30000 km to North Africa and Australia, respectively. Only 17% of our sample fly to long-haul destinations. SI figure 6 depicts the differences in sample average for long-haul air travel footprint, between 0.6 and 1.9 tCO2eq/cap for an average flight distance of 5000 and 12500 km/return flight. The differences in footprints become quite substantial for individuals who report more than 2 return flights a year (90th and 95th p).



SI Figure 6: Footprint ranges by various long-haul distance assumptions.

Prior to this study, Ivanova and colleagues developed household carbon footprint inventory for 177 regions in 27 EU countries (SI table 13)[7]. Their analysis calculated consumption-based emissions using data from consumer expenditure surveys and environmental and trade accounts from the EXIOBASE 2.3 multiregional input-output database. The spatial coverage of the study was based on the Nomenclature of territorial units for statistics (NUTS) regions [87], where the majority of footprinting was done at the NUTS 2 regional level, or the basic regions for the application of regional policies. While the regional analysis by Ivanova and colleagues (2017) generally cover larger regions than the ones sampled by the current study, there is quite a significant geographical overlap. Both studies include the NUTS 2 regions, Galicia (Spain) and Lazio (Italy), and the NUTS 1 region, Saxony-Anhalt (Germany), directly and should, thus, have the same geographical coverage with respect to these regions. There is a slight difference for the Romanian sample which covers the Banat-Timis region (Timiş County) in the GLAMURS survey, which lies within the larger "West Romania" region studied by Ivanova et al. (2017). Below we compare regional averages by consumption domains. We exclude the initiative samples for the purpose of this validity check.

Regional Name	Consumption category	Our study means (95% CIs), tCO_2eq	Ivanova et al. (2017), tCO_2eq
Galicia	Food	3.1 (2.5 - 3.7)	2.5
	Clothing	0.2 (0.1 - 0.2)	0.4
	Housing	1.9 (1.8 – 2.1)	1.2
	Transport	3.8 (3.3 – 4.2)	3.0
Banat-Timis	Food	2.0 (1.9 - 2.2)	1.8
	Clothing	0.2 (0.2 - 0.3)	0.1
	Housing	1.5 (1.3 - 1.7)	1.3
	Transport	3.6 (2.7 – 4.5)	1.6
Lazio	Food	1.6 (1.5 - 1.7)	1.5
	Clothing	0.3 (0.3 - 0.3)	0.6
	Housing	2.4 (2.2 - 2.7)	2.1
	Transport	4.2 (3.5 – 4.8)	3.3
Saxony-Anhalt	Food	2.4 (2.3 - 2.5)	1.5
	Clothing	0.4 (0.3 - 0.4)	0.5
	Housing	3.2 (2.8 - 3.5)	3.6
	Transport	3.9 (3.0 – 4.9)	3.8

SI Table 13: Validity check of footprint results by case study and consumption domain reporting 95% confidence intervals. Source: GLAMURS survey and Ivanova et al. (2017)

The difference between the food totals vary with less than a ton CO_2eq across all regions with a relative difference of up to 34%. The largest differences occur for "Other food" consumption, which is more susceptible to monetary outliers in our study. The absolute differences between the clothing estimates amount to less than 0.3 tCO_2eq across regions, though outside of the 95% CI of our results for most sub-regions. With the exception of the Romanian sample, our calculations are consistently lower than the prior regional analysis. A potential explanation is that in the survey we control for the second-hand share of clothing consumption as no discounting of second-hand purchases was carried out by Ivanova et al. (2017).

In absolute terms the housing differences vary up to 0.6 tCO_2eq. The divergence may be related to the method of calculation, e.g. uncertainty associated with the regression coefficients produced with TABULA data. Other factors that may play a role include seasonality of consumption, open-endedness of questions about fuel and electricity consumption, difficulty to answer or lack of knowledge about characteristics of dwelling etc. In analysis of uncertainty in household energy footprints, Min and Rao[88] find the uncertainty to be higher than 20% of footprints at most income levels in analysis of India and Brazil. A list of sources of uncertainty is provided including uncertainty from consumer expenditure surveys, bridging to MRIO, the MRIO model and the energy extensions[88] (in the context of the regional CES-MRIO study[7]).

Electricity comprised about 25% of average energy use in our sample, which matches Eurostat's breakdown of final energy consumption for the residential sector for EU-28[89]. Space heating accounts for about 63% of energy use in our sample and 64.7% for EU-28[89]. Gas and oil make up for 58% of heating in EU-28[89], and a bit less than 56% in our sample. Water heating contributes to 12% of annual energy consumption according to own estimates and 14.5% for EU-28 according to Eurostat[89].

The highest differences in terms of footprint results appear for the domain of transport, with the biggest driver being air travel. Air transport sectors are potentially more affected by residents' spending abroad and international travel, which may bring about higher uncertainty of results[90]. Compared to IO studies[7,91], our emission estimates for the transport domain seem overstated. Compared to a study utilizing the German travel survey[22] (with uncertainty in the travel survey in the order of a few percentage), our land-based transport estimates seem low, particularly for car and public transport (SI table 12). Similarly, a Finish study of the Helsinki Metropolitan Area using siftGIS (a public participation GIS method that combines online questionnaires with interactive maps) finds the average travel-related emissions to range between 4.1 and 4.9 tCO_2eq/cap by different urban zones[92]. Differences in results are likely due to assumptions concerning long- and short-lived GHGs[91], consumption assumptions and uncertainties[21], and the application of LCA data[91].

Birnik (2013) synthesized a set of literature-derived carbon footprint calculation principles concerning how personal carbon footprints should be determined. We list the principles in SI Table 14 and use them to evaluate our own carbon footprint calculations. Our calculator fulfills the majority of literature-derived principles with a few exceptions. We address these below.

With regards to P5, we have intentionally avoided to estimate consumption-based GHG emissions based on income, as we were interested in studying the independent effect of income on carbon footprints. In terms of P12 "Comprehensive footprints", our calculator considers consumption of clothing beyond the main categories of food, housing and transport. At the same time, our calculations omit additional consumption of manufactured products and services. We decided to only evaluate the rebound potential based on behavioral characteristics (rather than solely income-derived estimates). Similarly, in P8 "Housing emissions", we have excluded energy use and emissions associated with the construction of dwellings, although we have discussed the share of expected omitted impacts.

	Area	Principle: A personal carbon calculator should …	Own evaluation
1	GHG	Estimate emissions relating to carbon dioxide, methane and nitrous oxide	YES
2	GWP	Base conversions to carbon dioxide equivalents on 100-year GWP conversion factors	YES
3	Consumption data	Estimate consumption based footprints regardless of where production takes place	YES
4	Income/consumption adjustment	Allow users to adjust for income or consumption level instead of only using national averages	YES
5	Income/consumption adjustment	Adjust the relative distribution of consumption categories as a function of income level	NO
6	Household size	Adjust for the number of people living in the household	YES
7	Housing emissions	Allow users to model their housing emissions in detail	YES
8	Housing emissions	Capture emissions from household energy use as well as emissions from furnishings, appliances, building material and maintenance of buildings	NO
9	Food emissions	Allow users to model their food-related emissions in detail	YES
10	Transportation emissions	Allow users to model their transportation-related emissions in detail	YES
11	Transportation emissions	Allow users to include radiative forcing of flights when modelling flight emissions	YES
12	Comprehensive footprints	Provide a comprehensive footprint including allocating emissions for a variety of consumption categories	YES/NO
13	Emission factors	Base calculations on up-to-date and country/region specific emission factors whenever possible	YES

SI Table 14: Carbon footprint calculation principles and own evaluation. Source: [93]

Analysis

Model background

	Direction	Description of effect	Sources
Income and expenditure	(+)	Rising income increases purchasing power, but may reduce carbon intensity of consumption patterns	[94–99]
Household size	(-)	Household members share electrical appliances and require less individual living space (-), tendency to own multiple cars (+)	[94–96,98–100]
Gender	-/+	Differences in energy use and time use	[92,99]
Age	-/+	Older people less likely to adopt carbon-saving technologies; confounding effects with income found; time use differences	[99,100]
Educational level and environmental knowledge	-/+	Greater emphasis on environmental knowledge assumed; social status redesign of preferences and consumption	[94,96,99–101]
Urban-rural typology and population density	-/+	More compact form, location, higher impacts from food, leisure travel and manufactured products. When it comes to international travel, the highest levels of emissions are generated by residents of central urban areas (almost complete offset)	[7,92,95–97,99,100,102,103]
Relationship status	-/+	Time-use, number of children differences	[94]
Dwelling size	+	Larger dwelling use more energy	[94]
Dwelling type	-	Apartments have lower energy needs	[96,97,100]
Heating sources	-/+	Availability of district heating	[97]
Car ownership	(+)	Carbon intensive relative to alternative transport modes, car-free households associated with higher other consumption	[92,95,104]
Travel variables	-/+	Travel variables are generally inelastic with respect to change of the built environment. Still combined effects could be quite large	[105]
Working hours	(-)	Very high workload may lead to reduction of participation in leisure and family travel	[92]
Motivational factors	(-)	Limited evidence; less importance than income and physical factors. A strong effect of environmental concern on emissions, where the coefficient was the smallest for housing and the largest for mobility and food61; psychological factors can affect overall consumption levels, e.g. due to strong environmental value commitments	[106–108]
Environmental self-identity	(-)	environmental self-identity predicts pro-environmental behavior, ambiguous role in predicting carbon footprint	[109]
Rebound effects		Reducing of emissions in one domain and increase of emissions in other	[99,104]

SI Table 15: Literature review of considered socio-demographic, attitudinal and contextual effects.

Most prior assessments of environmental impacts considered variables like income, household size, sociodemographic variables (education, age, etc.), and some related psychologically relevant concepts, e.g. well-being or environmental identity measures (see SI table 15).

Robustness and sensitivity check

We reported different measures of collinearity (variance inflation factor (VIF) and tolerance values). As a rule of thumb, variables with VIF values greater than 10 may merit further investigation, as they may point to multicollinearity issues [110]. A tolerance value lower than 0.1 is comparable to a VIF of 10. We reported the 10 variables with highest VIF values across carbon intensity OLS models (same variables included in the behavioral models). SI table 16 reports the highest VIF values, all of which are below the threshold of 10.

	Total carbon intensity for mobility			Total carbon intensity for shelter		
	Variables	**VIF**	**1/VIF**	**Variable**	**VIF**	**1/VIF**
1	LMOB_DIS	7.20	0.139	SH	7.58	0.132
2	LMOB_DIS sq.	7.05	0.142	DSIZE	6.85	0.146
3	CAR_ONE	3.14	0.318	WH	2.75	0.363
4	CAR_MANY	3.05	0.328	REGION_ES	2.67	0.375
5	REGION_ES	2.29	0.436	REGION_IT	2.31	0.432
6	REGION_IT	2.16	0.463	REGION_RO	2.16	0.463
	Mean VIF	**2.28**		**Mean VIF**	**2.13**	

SI Table 16: Variance inflation factors and tolerance value to infer about multicollinearity in the regression analysis in table 3 and table 5.

Odds ratios are reported in SI table 17 and 19. For easy interpretation, one needs to calculate the exponent of the coefficient, producing how the odds to choose the dependent variable alternative over the base outcome change with a one unit change in the independent variable [111].

A daily trip in the MLOGIT models refers to the distance of a daily trip with a specific travel mode, not the complete distance travelled by an individual per day. We use the FE model as a robustness check, with the main effects being unchanged (SI table 17). Due to lack of variance in the trip mode, a number of individuals have been dropped in the FE model. This is a significant limitation of this model as it excludes respondents who, for example, only use active transportation, which could otherwise provide useful policy insights. One cannot evaluate marginal effects in a fixed-effect multinomial logit as the unobserved heterogeneity vector α is not estimated [111].

MOBILITY:	Pooled MLOGIT (β/se)		FE MLOGIT (β/se)	
	Active transport	Public transport	Active transport	Public transport
LMOB_DIS (km/trip)	*-0.069****	*0.011****	*-0.088*	*0.017*
	(0.01)	*(0.00)*	*(0.008)****	*(0.005)****
LMOB_DIS sq.	*0.000****	*-0.000****	*0.000*	*-0.000*
	(0.00)	*(0.00)*	*(0.000)****	*(0.000)****
WORK	*0.314****	*0.623****	*0.346*	*1.088*
	(0.09)	*(0.11)*	*(0.122)****	*(0.156)****
CAR_ONE	-2.096***	-3.080***		
	(0.20)	(0.23)		
CAR_MANY	-1.393***	-1.833***		
	(0.19)	(0.21)		
MINI_ATT	0.065**	0.083**		
	(0.03)	(0.04)		
MINI_USE	0.010	-0.048		
	(0.02)	(0.03)		
RURAL	-0.306***	-0.334***		
	(0.06)	(0.07)		
HHSIZE	0.035*	-0.003		
	(0.02)	(0.03)		
FEMALE	-0.030	0.337***		
	(0.09)	(0.12)		
AGE	-0.001	-0.014***		
	(0.00)	(0.01)		
EDUC	0.138***	-0.044		
	(0.04)	(0.05)		
MARRIED	-0.338***	-0.526***		
	(0.10)	(0.13)		
INCOME	-0.070	-0.019		
	(0.05)	(0.06)		
WHRS	0.112***	0.150**		
	(0.04)	(0.06)		
Log likelihood	**-3663.1308**		**-1274.4044**	
Pseudo R²	**0.1723**		**0.1376**	
N trips	**4,393**		**3,112**	
N individuals	**1,394**		**770**	

SI Table 17: Pooled and fixed-effects multinomial logistic regressions. Base outcome: Private motorized transport (car or motorbike). Data for regressors in italics is collected on the trip level, and for the rest - on respondent level. Active transport = walk/bike/e-bike; Public transport = bus/tram/underground/train. *p<.1, ** p<.05, *** p<.01;

SI table 18 presents a sensitivity check for some of our results focusing on the number of trips, rather than GHG emissions. First, we conducted logistic regressions with a binary dependent variable, taking a value of zero for a zero number of trips and a value of one for a positive number of return trips. This was to regard the largely non-normal distribution of dependent variables with a significant number of zero-trips: car work trips (60%), car private trips (34%), short-haul flights (53%) and long-haul flights (83%). Second, we complemented the analysis with OLS regression results including only results with a positive number of trips. We find the factors to determine the likelihood of having car trips – work or private – are somewhat similar. Car ownership and use (CAR_ONE and CAR_MANY), and rural context (RURAL) increased the likelihood of having car trips. Females, non-married, low-income and long-work-hours were less likely to have car work trips. Long-work-hours were more likely to have car private trips. Focusing on the sub-sample with positive number of car trips, the selected variables have much lower power to explain variations in car trips. For private trips, single- and multi-users have 89 and 72 more car trips. Larger household size decreases the likelihood of flying, with coefficients significant at 10% and 5% for short- and long-haul flights, respectively. Those with higher income and education more likely to fly, confirming our conclusions from table 3 for both short and long flights. The explanatory power of the OLS models for the sub-sample that flies is rather low.

Positive number of trips	Car work trips		Car private trips		Short flights		Long flights	
	LOGIT	**OLS**	**LOGIT**	**OLS**	**LOGIT**	**OLS**	**LOGIT**	**OLS**
CAR_ONE	3.987***	98.907	2.632***	89.282***	-0.178	-0.557	-0.268	0.268
	(0.52)	(147.50)	(0.23)	(22.96)	(0.21)	(0.53)	(0.25)	(0.67)
CAR_MANY	2.671***	113.748	2.011***	71.676***	-0.129	-0.504	-0.367	0.440
	(0.52)	(121.19)	(0.22)	(22.35)	(0.20)	(0.58)	(0.24)	(0.81)
MINI_ATT	-0.011	-40.113	-0.001	3.934	0.101***	0.029	-0.001	0.006
	(0.04)	(24.89)	(0.04)	(3.30)	(0.04)	(0.09)	(0.05)	(0.10)
MINI_USE	-0.007	31.249	0.029	-2.227	-0.005	0.174	0.062	0.261
	(0.04)	(25.28)	(0.04)	(3.17)	(0.03)	(0.12)	(0.04)	(0.21)
RURAL	0.361***	99.081*	0.366***	13.352*	-0.022	-0.245	0.094	-0.234
	(0.09)	(56.15)	(0.10)	(6.85)	(0.08)	(0.18)	(0.10)	(0.20)
HHSIZE	-0.050	21.828	0.019	-2.604	-0.074*	0.033	-0.143**	-0.068
	(0.06)	(25.35)	(0.04)	(2.13)	(0.04)	(0.10)	(0.07)	(0.25)
FEMALE	-0.369**	-10.187	0.098	15.096	-0.050	-0.860***	-0.041	-0.837
	(0.15)	(78.86)	(0.14)	(11.12)	(0.12)	(0.33)	(0.15)	(0.53)
AGE	-0.001	-1.966	0.009	0.098	-0.019***	0.014	-0.008	0.020
	(0.01)	(3.66)	(0.01)	(0.44)	(0.00)	(0.02)	(0.01)	(0.02)
EDUC	0.031	43.037	-0.039	8.922	0.269***	0.227*	0.211***	0.061
	(0.07)	(48.44)	(0.07)	(5.67)	(0.06)	(0.14)	(0.08)	(0.44)
MARRIED	0.450***	-37.064	0.300*	11.068	0.068	0.031	0.117	-0.973
	(0.17)	(61.91)	(0.16)	(12.35)	(0.13)	(0.35)	(0.17)	(0.73)
INCOME	0.188**	68.464	0.109	-5.038	0.288***	0.227	0.205***	-0.242
	(0.08)	(50.49)	(0.07)	(6.51)	(0.06)	(0.18)	(0.07)	(0.21)
WHRS	-1.268***	-4.124	0.150**	28.792***	0.018	0.032	0.021	-0.227
	(0.08)	(29.08)	(0.07)	(5.74)	(0.06)	(0.12)	(0.07)	(0.30)
Log likelihood	**-619.11**	**-**	**-702.14**	**-**	**-909.43**	**-**	**-601.81**	**-**
Adjusted (Pseudo) R^2	**0.36**	0.000	**0.16**	0.060	**0.07**	0.050	**0.05**	0.031
N individuals	**1409**	623	**1409**	1017	**1409**	653	**1409**	224

SI Table 18: Sensitivity check on number of trips. In the logistic regression (LOGIT) models, the dependent variable is binary, taking value of zero for no trips and 1 for a positive number of trips. The OLS models focus specifically on the variable relationships in the sub-sample of respondents who report a positive number of trips, adopting the continuous variable of annual number of trips with the particular travel mode as dependent variable.

	SHELTER: Pooled MLOGIT (β/se)							**Marginal Effects (Probability)**			
	SH ELEC (1)	**SH DIST (2)**	**SH OIL/GAS (3)**	**SH NOT (5)**	**WH ELEC (1)**	**WH DIST (2)**	**WH OIL/GAS (3)**	**WH ELEC (1)**	**WH DIST (2)**	**WH OIL/GAS (3)**	**WH RENEW (4)**
ELEC_USE	0.066**	-0.012	0.004	-0.107	-0.001	-0.047	-0.011	0.001	-0.003	0.001	0.001
	(0.03)	(0.05)	(0.03)	(0.08)	(0.01)	(0.04)	(0.01)	(0.001)	(0.004)	(0.003)	(0.001)
SH_USE	0.050*	-0.047	0.043**	0.056**	0.034**	-0.016	0.021*	0.002	-0.003*	0.003	-0.002
	(0.03)	(0.03)	(0.02)	(0.03)	(0.02)	(0.02)	(0.01)	(0.001)	(0.002)	(0.002)	(0.001)
WH_USE	-0.151	0.205	-0.401	0.509	-0.273	-0.301	-0.250	-0.005	-0.008	-0.011	0.024
	(0.59)	(0.60)	(0.54)	(0.72)	(0.43)	(0.45)	(0.34)	(0.031)	(0.030)	(0.043)	(0.031)
DSIZE	-0.014**	-0.000	-0.006***	-0.007*	-0.004**	-0.001	-0.004**	-0.000	0.000	-0.000	0.000
	(0.01)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.000)	(0.000)	(0.000)	(0.000)**
DTYPE	0.396***	0.773***	0.429***	0.758***	0.203**	0.569***	0.150*	0.003	0.039***	-0.021	-0.020
	(0.15)	(0.15)	(0.12)	(0.19)	(0.10)	(0.12)	(0.08)	(0.008)	(0.009)	(0.011)*	(0.007)***
CONSTR	0.016	-0.078	0.024	0.162	-0.017	0.014	0.000	-0.002	0.001	0.001	0.000
	(0.14)	(0.12)	(0.10)	(0.20)	(0.10)	(0.11)	(0.09)	(0.007)	(0.007)	(0.011)	(0.008)
EPROD	-0.990	-2.093*	-0.919	-12.726***	-0.877	-1.210	-1.132**	0.013	-0.026	-0.088	0.102
	(1.03)	(1.25)	(0.67)	(0.96)	(0.67)	(0.88)	(0.55)	(0.052)	(0.067)	(0.084)	(0.049)**
REFURB	0.080	0.054	0.164**	0.211	-0.003	-0.020	0.051	-0.004	-0.005	0.012	-0.003
	(0.11)	(0.11)	(0.08)	(0.16)	(0.08)	(0.09)	(0.07)	(0.006)	(0.006)	(0.009)	(0.006)
EINI_ATT	-0.051	-0.140	-0.045	0.012	-0.005	-0.011	0.074	-0.006	-0.006	0.016	-0.005
	(0.11)	(0.10)	(0.08)	(0.15)	(0.08)	(0.08)	(0.06)	(0.006)	(0.005)	(0.008)*	(0.006)
EINI_USE	-0.025	0.063	-0.025	-0.270**	0.042	0.050	-0.080	0.010**	0.009*	-0.023	0.004
	(0.09)	(0.08)	(0.07)	(0.13)	(0.07)	(0.07)	(0.06)	(0.005)	(0.005)	(0.008)***	(0.005)
RURAL	-1.084***	-0.783***	-0.950***	-1.343***	-0.118	-0.292	-0.183	0.006	-0.013	-0.010	0.018
	(0.23)	(0.22)	(0.16)	(0.41)	(0.19)	(0.20)	(0.14)	(0.015)	(0.014)	(0.020)	(0.013)
HHSIZE	-0.024	0.044	-0.110	-0.045	0.013	-0.033	0.044	-0.002	-0.006	0.010	-0.003
	(0.08)	(0.07)	(0.10)	(0.12)	(0.11)	(0.11)	(0.06)	(0.009)	(0.008)	(0.010)	(0.006)
FEMALE	0.082	0.071	0.329	0.668	0.079	-0.170	-0.067	0.015	-0.012	-0.010	0.006
	(0.32)	(0.30)	(0.24)	(0.51)	(0.26)	(0.26)	(0.21)	(0.020)	(0.017)	(0.027)	(0.018)
AGE	-0.001	0.018	0.014	-0.022	0.009	0.021*	0.016*	-0.001	0.001	0.001	-0.001
	(0.01)	(0.01)	(0.01)	(0.03)	(0.01)	(0.01)	(0.01)	(0.001)	(0.001)	(0.001)	(0.001)*
EDUC	-0.161	-0.114	-0.062	-0.227	0.112	0.044	0.072	0.005	-0.002	0.003	-0.007
	(0.16)	(0.14)	(0.11)	(0.21)	(0.13)	(0.12)	(0.10)	(0.009)	(0.008)	(0.013)	(0.009)
MARRIED	0.014	-0.483	0.236	-0.268	-0.555*	-0.651*	-0.087	-0.043*	-0.046**	0.067	0.022
	(0.39)	(0.38)	(0.29)	(0.65)	(0.33)	(0.36)	(0.27)	(0.023)	(0.023)	(0.033)**	(0.025)
INCOME	0.214	0.250	0.266*	-0.473*	-0.001	0.058	0.011	-0.002	0.004	-0.001	-0.002
	(0.19)	(0.18)	(0.14)	(0.28)	(0.14)	(0.13)	(0.10)	(0.010)	(0.009)	(0.014)	(0.009)
WHRS	-0.152	-0.258*	-0.111	-0.133	-0.110	-0.274**	-0.156	0.004	-0.013	-0.006	0.015
	(0.16)	(0.15)	(0.12)	(0.24)	(0.13)	(0.14)	(0.11)	(0.009)	(0.009)	(0.014)	(0.010)
Log Likelihood	**-974.5476**				**-1124.1462**						
Pseudo R^2	**0.2368**				**0.1293**						
N individuals	**1,133**				**1,235**						

SI Table 19: Pooled multinomial logistic regressions, odds ratios and marginal effects. Base outcome for space heating: (4) SH by renewables (pellets/firewood, solar-thermal heater) or electric/gas heater; base outcome for water heating: (4) WH by renewables (pellets/firewood, solar-thermal heater) or electric/gas hot water tank. Other heating options: (1) by electricity, (2) by district heating, (3) by gas and oil, (5) not heating. In the case of WH, heating by renewables and not heating have been combined due to too few observations not heating. We only perform marginal effects for the observations that have selected a single heating source (99% for WH). Regional controls included. Robust errors included. *p<.1, ** p<.05, *** p<.01

Other consumption

Carbon Footprint	**Food**	**Clothing**
LMOB_DIS (km/day)	0.000	0.000
	(0.00)	(0.00)
LMOB_DIS sq.	0.000	0.000
	(0.00)	(0.00)
ACTIVE	-0.100**	-0.226*
	(0.05)	(0.14)
PUBLIC	-0.022	-0.022
	(0.04)	(0.12)
AMOB_SHORT	0.010**	0.042***
	(0.00)	(0.01)
CAR_ONE	0.126***	0.359**
	(0.05)	(0.14)
CAR_MANY	0.099**	0.203
	(0.04)	(0.14)
MINI_ATT	-0.025***	0.018
	(0.01)	(0.02)
MINI_USE	-0.008	-0.016
	(0.01)	(0.02)
ELEC (kWh/day)	0.004*	0.010**
	(0.00)	(0.00)
SH (kWh/day)	0.005***	0.008
	(0.00)	(0.00)
WH (kWh/day)	-0.084	0.006
	(0.06)	(0.15)
DSIZE	-0.000**	-0.001
	(0.00)	(0.00)
DTYPE	-0.001	-0.027
	(0.01)	(0.03)
CONSTR	0.031***	0.036
	(0.01)	(0.03)
EPROD	-0.006	-0.396**
	(0.06)	(0.16)
REFURB	-0.010	0.027
	(0.01)	(0.02)
EINI_ATT	-0.010	-0.081***
	(0.01)	(0.02)
EINI_USE	0.002	0.005
	(0.01)	(0.02)
RURAL	-0.017	-0.052
	(0.02)	(0.05)
HHSIZE	-0.005	-0.073
	(0.02)	(0.05)
FEMALE	-0.147***	0.105
	(0.02)	(0.07)
AGE	0.003**	0.002
	(0.00)	(0.00)
EDUC	-0.035***	0.056
	(0.01)	(0.03)
MARRIED	0.049	0.063
	(0.03)	(0.09)
INCOME	0.050***	0.221***
	(0.01)	(0.03)
WHRS	-0.028**	0.037
	(0.01)	(0.03)
Adjusted R^2	0.284	0.201
N individuals	1230	1127

SI Table 20: Effects on other consumption domains. The dependent variables, carbon footprint of food and clothing in logarithmic form (constant and regional controls included. ACTIVE and PUBLIC refer to the active and public travel share *p< .1, ** p < .05, *** p < .01

Co-benefits

For example, in the context of active and public travel such co-benefits include, e.g. improved health and physical activity [105,112–114], reduced social inequalities through healthy and affordable transportation means [112,115], reduced carbon lock-in [116], reduced noise, traffic congestion and pollution [117], and decreased pressure on public infrastructure [118]. Furthermore, a shift away from car use may free travel infrastructure budget and public space for roads and parking [119,120]. Green spaces, parking and zoning restrictions may also reduce urban noise, pollution and energy demand in buildings; promote connection with nature, social resilience, active community life and travel; and improve traffic safety [117,121,122]. Flexible work schemes and telecommuting may reduce commuting time (or working days), which has been noted to have a positive effect on psychological well-being [123] and the need for autonomy [124].

The shift towards renewables is associated with multiple benefits, e.g. health effects of reduced air pollution and climate change [122,125], innovation, employment and regional resilience through greater decentralization [126,127]. Nevertheless, one should be aware of the potential pitfalls including potential ecosystem and social costs, e.g. biodiversity loss, noise generation, unemployment and rising energy prices [126,127]. The shift to more energy-efficient and renovated housing brings about improvements in health and thermal comfort, and reductions in resource use, energy poverty and social inequalities [122,126,128].

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Article 4

Members of environmental grassroots initiatives reconcile lower carbon emissions with higher well-being

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See A-4.2 for Supplementary Information

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