Doctoral theses at NTNU, 2018:374

Gibran Vita

The Environmental Impacts of Human Needs and Lifestyles:

Connecting the global economy, natural resources and human well-being

Doctoral Thesis

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ISBN 978-82-326-3536-8 (printed version)
ISBN 978-82-326-3537-5 (electronic version)
ISSN 1503-8181

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Thesis for the degree of Philosophiae Doctor

Trondheim, November 2019

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Printed by Skipnes Kommunikasjon as

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Where is the knowledge we lose with information? Where is the wisdom we lose with knowledge?

-T.S. Eliot

Do you want to improve the world?

The world is sacred

It can't be improved.

If you tamper with it, you'll ruin it.

If you treat it like an object, you'll lose it.

-Lao Tzu

The Source of Life invigorated these ancient nations with the Water of Life, but later generations were swept aside because their way of life had lost its purity and resilience by ignoring and even negating the Source of Life.

-Holy Qur'an 6:1-9
Meditations by Lex Hixon

It's time for us as a people to start makin' some changes. Let's change the way we eat, let's change the way we live and let's change the way we treat each other…the old way wasn't working so it's on us to do what we gotta do, to survive.

-Tupac Shakur

You can play a shoestring, as long as you are sincere

-John Coltrane

To my beloved Gina & her cosmic dance

To my grandmas, abuelitas Chagua & Lilia

Preface

Ad Astra Per Aspera

The field of Industrial Ecology (IE) proposes a systems perspective on sustainability issues. It relies on a powerful set of analytical tools to understand human-nature relationships beyond the disjointed approaches of disciplinary silos. In practice, the field has focused on accounting tools to describe socio-economic metabolism and technical systems, while the role of human well-being and social systems remains beyond the boundaries of IE work.

Indeed, IE tools have been essential to mapping interlinkages between economic development and environmental problems. However, most IE solutions remain in the technological sphere or within the status-quo. Without losing its roots, IE has the potential to embed a stronger social perspective by drawing on the narratives and methods of social sciences. This is a natural step if industrial ecology is to shed light on sustainability pathways that are socially, technically and environmentally sound.

Sustainability science is inherently political. The research question, methodological approach and result interpretation are susceptible to the values and world views of the researcher. In my view, our role as scientists is to expand human consciousness into perceiving, understanding and assimilating the complexity and inter-connectedness of the world's needs and resources beyond the apparent. In this PhD, I make an effort towards holistic research while staying true to the roots of industrial ecology, without forgetting my own roots. My hope is to be of service to human and non-human life. In this case, my goal is to contribute to illuminating pathways towards more harmonious and flourishing life for all creation.

Gibran Vita
Trondheim, October 2018

Keywords

Figure 2 | Thesis keywords. Semi-quantitative word cloud showing the identity and frequency of terminology used in this thesis. Size of the word is weighted by the frequency of the term in thesis excerpts.

Graphical Abstract

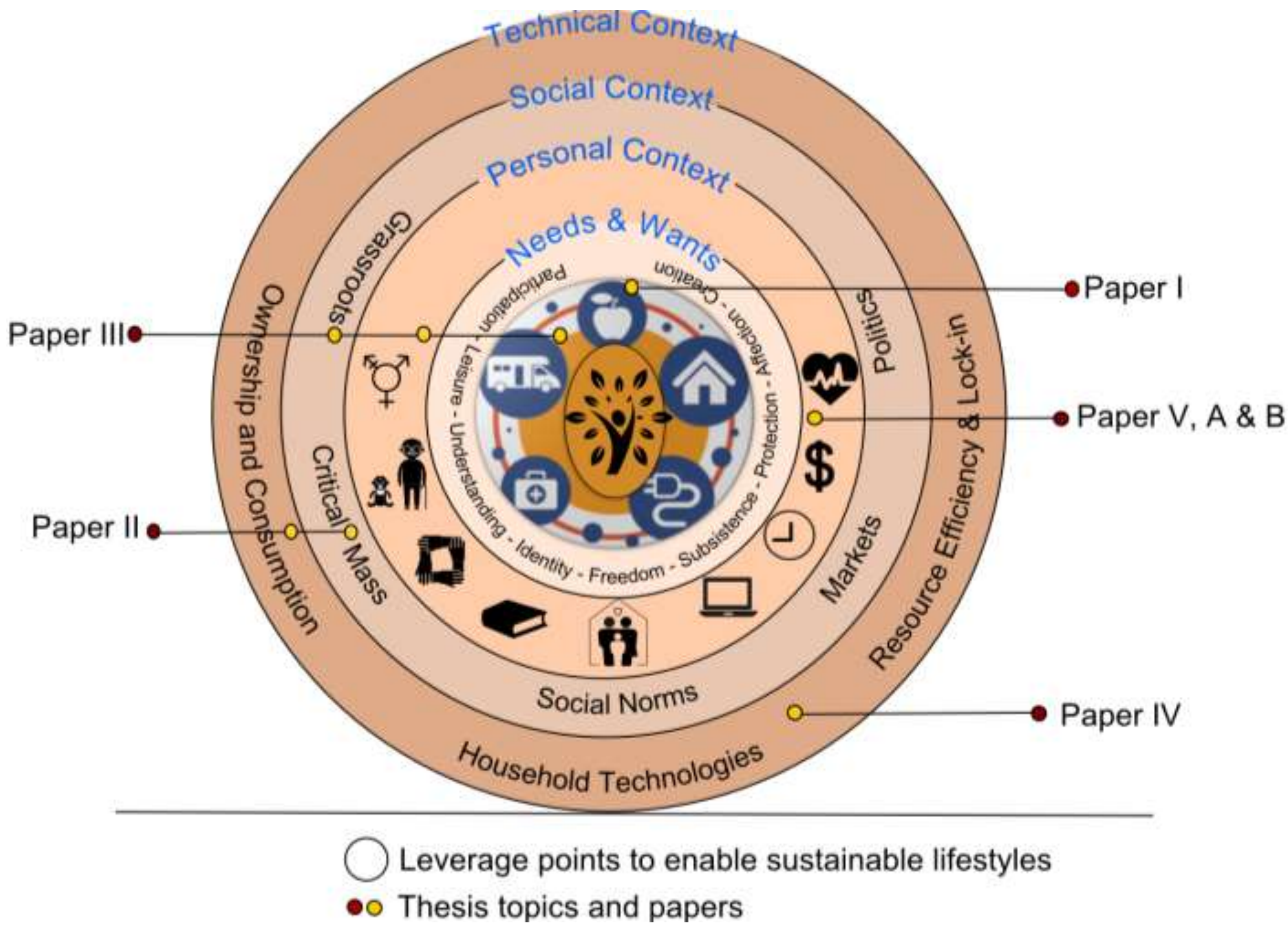


Figure 1 | Thesis graphical abstract. Topics and papers within "The Environmental Impacts of Human Needs and Lifestyles**:** *Connecting the global economy, natural resources and human well-being"*. All of the topics shown in the figure are discussed in the light of their environmental relevance. Source: The author. All icons are of free license (vecteezy.com).

Abstract

Industrial ecology tools have a role in informing the United Nations Sustainable Development Goals. However, a more socially meaningful industrial ecology would have a stronger impact. Identifying the most feasible options calls for multidimensional systems perspectives. This research provides insights into opportunities and challenges to reconcile lifestyles, human needs and planetary well-being. This work assesses multiple environmental and social indicators to analyze synergies, trade-offs and lock-ins within the human-economy-nature triad. It views fundamental human needs and lifestyles at the center of socio-economic metabolism.

Paper I connects the framework of fundamental human needs to global carbon emissions. The needs for *subsistence* and *protection* require the most resources but remain largely unsatisfied. Most objective indicators of need satisfaction show a satiation trend with respect to footprints, while subjective indicators show no relationship, except for *freedom* and *creation*. This study signals the importance of considering both subjective and objective satisfaction to assess quality of life-impact relationships at the needs level. In this way, resources could be strategically invested where they strongly yield social outcomes, and spared where non-consumption satisfiers could be more effective. The paper sets the basis to measure the impact of fundamental human needs while jointly assessing their satisfaction.

Paper II introduces an input-output model to simulate scenarios of alternative consumption and production. It draws on participatory methods of backcasting to build lifestyles scenarios based on citizens' visions. The contribution is to provide a multi-indicator outlook of the sustainability implications of an assortment of sufficiency and green consumption options. We find that reducing transport by working from home and commuting actively, local and peer-to-peer services, durable fashion, and lower food waste are *sufficiency* options with significant mitigation potential. We find potential in shifting current expenditure towards *green consumption* options such as renting, sharing and repairing manufactured products, adopting passive house standards and eating plant-based diets.

Paper III finds that members of sustainability-focused grassroots initiatives have 15% lower carbon footprints and higher life satisfaction compared to their socio-economic counterparts. The carbon footprint reduction by grassroots members are even larger for less context-constrained domains: 43% lower for food and 86% lower for clothing. The research shows the potential of grassroots initiatives to reconcile planetary and human well-being. The method bridges sound environmental impact principles of industrial ecology with social science tools such as behavioral surveys and psychological health. While grassroots might have a minor direct influence on total emissions, they can influence)society through changing narratives of consumption and self-providing sustainable goods.

Paper IV provides a perspective on the direct and indirect energy utilized by household durable equipment. We calculate the cradle-to-gate energy footprints of 200 goods across the 44 largest economies and five world regions for the period 1995-2011. We find durable goods to be responsible for 10% of the global final energy embodied in household consumption. However, the services and consumables complementary to durables amount to 8% global final energy footprints, while the fuels and electricity to operate durables amount to 51%. Thus, two-thirds of the global household final energy is associated with durable goods

Paper V combines nutrition sciences that model individuals' energetic metabolism as a function of biophysical characteristics, with epidemiology and demographic studies that provide evidence for large shifts in height, weight, life expectancy and age structure worldwide. The paper shows the disaggregated effects of short term human evolution for food demand. Across countries over the period of 1975 and to 2014, individuals' weight gains ranged between 6-33% and energy needs increased between 0.9-16%. Globally, food energy increased by 129%. Population growth contributed with 116%, weight and height gains by 15%, while the aging phenomenon counteracted the rise in energy needs by 2%. This net additional 13% demand added only by larger human mass (beyond population numbers) corresponded to the food demands of 286 million global average adults. This research has implications for previous calculations of sufficiency and food availability: a given population size today can require up to 16% more food within 40 years from now. What previous analyses have estimated as rising food availability could actually be offset by increasing human mass.

About this work

This research was conducted in the context of transdisciplinary projects funded by the European Commission FP7 framework. My role was to collaborate with disciplines including economics, psychology, participatory research, computer science, agent-based modelling, futurism, etc. for a holistic assessment of the environmental impacts of present and future consumption, human needs, grassroots initiatives and lifestyles.

The GLAMURS (Green Lifestyles, Alternative Models and Upscaling Regional Sustainability) project applied theoretically-based and empirically-grounded frameworks to understand the main obstacles and prospects for sustainable lifestyles in Europe. I was responsible for the work package "Environmental impact assessment of present and potential future lifestyle and economic alternatives", by modelling environmental impacts from multiple-scopes: nations, regions, individuals and scenarios. I participated across work packages with the task of cross-pollinating industrial ecology with other disciplines (glamurs.eu). Grant Agreement: 613420.

The DESIRE (Development of a System of Indicators for a Resource Efficient Europe) project develops and applies an optimal set of indicators to monitor European progress towards resource-efficiency. My contribution was to develop a framework that links market products to human needs and estimate their environmental impact (http://fp7desire.eu/) as part of the "Novel reference indicators: Beyond GDP and value added" work package. Grant agreement: 308552.

This thesis was submitted to the Norwegian University of Science and Technology (NTNU) as a partial fulfillment of the requirements for the degree of Philosophiae Doctor, in the period from November 2015-August 2018 under the supervision of Prof. Richard Wood, Prof. Edgar G. Hertwich and co-supervised by Dr. Konstantin Stadler. The work was mainly conducted at the Industrial Ecology Programme, Department of Energy and Process Engineering.

Research stays

The work was partially conducted through the following research stays:

Cooperation with Dr. Christopher Jones and Prof. Daniel Kammen at the Cool Climate Network from Energy and Resource Group, Berkeley, University of California, funded by the Peder Sather Center Grant (04.2016-06.2016) http://coolclimate.berkeley.edu/

Cooperation with Prof. Edgar G. Hertwich at the Yale School of Forestry & Environmental Studies, New Haven, USA (06.2016) through the Peder Sather Center Grant.

Cooperation with Dr. Narasimha Rao and Dr. Jihoon Min at the Energy Group at the International Institute for Applied Systems Analysis (IIASA), in Vienna. As part of the Young Scientists Summer Program 2017 (YSSP), funded by the Norwegian Research Council. (05.2017-08.2017). http://www.iiasa.ac.at/

Acknowledgements

I would like to thank my family for their patience with my nomadic life, for trusting my path and staying always near despite the distance. Gracias familia, por siempre estar ahí y por darme la fuerza para nunca rendirme.

I was fortunate to be guided by two front runners in the field of Industrial Ecology: Richard Wood and Edgar Hertwich, who dexterously supervised this research. I thank you greatly for the opportunity to undertake this challenge, and for your trust, patient guidance and invaluable support to complete it. I thank my co-supervisor Konstantin Stadler for his unique combination of pragmatic and humoristic advice, which was often most needed.

I thank all my co-authors for their insightful sharing, assertive questioning and constant motivation, all of which improved my research and enriched my journey. I thank you Diana, for sharing most of our PhD adventures; for your courage, determination and laughter attacks despite the challenges during our project work. I thank all my colleagues and co-authors from the GLAMURS and DESIRE consortiums, composed of an assortment of disciplines and personalities, for expanding my views on sustainability. Thank you Arkaitz, Karen, Ricardo, Adina, Giuseppe and Jaco, for your contributions to this research. I deeply enjoyed collaborating with the Indecol-MFA group, where technical methods and philosophy always naturally intertwine when conversing with Daniel, Felipe and Avijit. Thank you!

I thank Narasimha and Jihoon, whose research inspires me, for welcoming into the Energy Group at IIASA during a very fruitful summer. Thank you Shonali, Fricko and Joeri, for your insightful inputs, and the thanks to the wonderful YSSP-2017 cohort for your enthusiastic friendship during our time in Vienna. Thanks to Chris Jones and Dan Kammen for having us at the ERG group, UC Berkeley. It was a great experience and I deeply appreciated collaborating with Diego, Sergio, Kat and Tomek. Same goes for the friends at Yale University, who I always look forward to encounter: Tamar, Peter, Benjamin and Ranran.

I thank EVERYONE at INDECOL, I appreciate ALL of you and hope to always remain in touch. Thank you Sarah and Eivind for your solidarity. Thank you NTNU-EPT admin and IT dept., for the technical and financial means you provided. Thanks to my master students, for reminding me to keep research fresh and curious. Thank you Kam, Angela and Christine, for proofreading my texts and improving my Spanglish. I would also like to acknowledge all the naysayers along my path. I surely learned more from you than what you taught me.

To my friends here and scattered throughout the globe, thanks for sharing our lives, understanding my (hopefully) fleeting PhD-madness and for being fully present whenever the time has been right: the childhood mexas who stayed and left, la psico, the LF misfits, the MINDers, mentors and all the friends along the way.

Thank you Yumina, for constantly bringing me back to the important things in life.

Contents

Publications list
Primary Publications

I. **Vita,G**.;Hertwich,E.G.; Stalder,K.; Wood,R. (2018) Connecting global emissions to fundamental human needs and their satisfaction. *Environmental Research Letters.*

Author contribution: Research design, framework development, analysis, visualization, and writing.

II. **Vita, G**; Lundström, R; Quist, J.; Stadler, K.; Ivanova, D.; Wood, R. and Hertwich, E.G. Sustainable lifestyle scenarios to curb European environmental impact: Connecting local visions to global consequences (2018). *Under review with Ecological Economics.*

Author contribution: Research design, modelling, analysis, visualization, and writing.

III. **Vita, G***. ;Ivanova, D*.; 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. (2018). *Under review with Environmental Research Letters* *Shared first authorship.

Author contribution: pilot and final survey design, carbon calculator model, analysis and article design, result discussion and writing.

IV. **Vita, G**.; Narasimha, R.; Usubiaga, A.; Min,J.; and Wood, R. The energy footprints of household durables, consumables and services: A global study from 1995 to 2011 (2018), in preparation. *Submitted*

Author contribution: Research design, framework development, analysis, visualization, and writing.

V. Vásquez, F*.; **Vita, G***.; Müller, D. Food security for an ageing and heavier population (2018). **Sustainability** *Shared first authorship

Author contribution: G.V. analyzed results and drafted the manuscript. F.V. and G.V. contributed equally to the literature review, analysis of results, generation of figures and tables, and writing of the manuscript.

Additional Publications

A) Ivanova, D.; **Vita, G**.; Steen-Olsen, K.; Stadler, K.; Melo, P.; Wood, R.; Hertwich, E. G. (2016) Mapping the carbon footprint of EU regions. Environmental Research Letters.

DOI: https://doi.org/10.1088/1748-9326/aa6da9

Author contribution: Research design, data collection, result discussion and manuscript editing.

B) Ivanova, Diana; **Vita, Gibran**; Wood, Richard; Lausselet, Carine; Dumitru, Adina; Krause, Karen; Macsinga, Irina; Hertwich, Edgar G.. (2018) Carbon mitigation in domains of high consumer lock-in. Global Environmental Change. vol. 52.

DOI: 10.1016/j.gloenvcha.2018.06.006

Author contribution: Research design, analysis, result discussion and manuscript editing.

Reports

C) **Vita, G**., Ivanova, D., Stadler, K., Kammerlander, M. & Alge, S. Deliverable 7.2: Environmental footprinting for case studies – tool and documentation. in *GLAMURS WP7: Environmental impact assessment of present and potential future lifestyle and economic alternatives* 1–88 (EU Comission FP7, 2016).

URL : http://glamurs.eu/wp-content/uploads/2016/08/WP7_Deliverable_7.2-1.pdf

D) **Gibran Vita**, Diana Ivanova, Johan R. Lundström, Alexander Tisserant, Konstantin Stadler, Jaco Quist, Sjak Smulders and Richard Wood. Deliverable 7.3: Analysis of current impact of lifestyle choices and scenarios for lifestyle choices and green economy developments. in *GLAMURS WP7: Environmental impact assessment of present and potential future lifestyle and economic alternatives* 1–208 (EU Comission FP7, 2016).
URL : http://glamurs.eu/wp-content/uploads/2017/01/WP7_Deliverable_7.3.pdf

E) Usubiaga, A., Schepelmann, P., Freyling, V., **Vita, G**., Stadler, K.,Wood, R., Hertwich, E., Van Bree, T., Brouwer, J., Berrelkamp, S. Beyond GDP resource efficiency. in *DESIRE-(Development of a System of Indicators for a Resource Efficient Europe-* (EU Comission FP7 Framework Program, 2015).
URL: http://fp7desire.eu/documents/category/3-public-deliverables

Posters and Conferences

F) **Vita, G**.; Narasimha,R.;Min,J.;Usubiaga,A.;Wood,R.;Hertwich,E.G. THE ROLE OF DURABLE GOODS IN LOCKING-IN ENERGY NEEDS: A global study of energy footprints of household goods from 1995 to 2011. Presented at the Gordon Research Conference in Les Diablerets, Switzerland, 2018. **Award for best student poster.**

G) **Vita, G**; Lundström, R; Quist,J.;Stadler,K.;Ivanova, D.; Wood,R. and Hertwich,E.G. Sustainable lifestyle scenarios to curb European environmental impact: Connecting local visions to global consequences. Presented at the SCORAI- Sustainable Consumption Research and Action Initiative in Copenhagen, Denmark, 2018. O**utstanding early career scholar paper**.

1. Introduction

Unlike most quests, pursuit for economic growth does not end when reaching a goal. Instead, constant growth is a goal in itself. Such an endeavor relies on the incessant transformation of natural and human capital into profitable commodities. Under this socio-economic paradigm, human needs are supposed to be satisfied as a consequence of a thriving economic apparatus.

Economic growth alone has not been a guarantee of satisfied human needs[1]. Nearly 1 billion people have risen above extreme poverty since 1990, earning above US$1.90[1] a day, driven mainly by high economic growth in China and India. Yet over three billion people live on less than $2.50 a day, 1.6 billion people live without electricity, 1.1 billion have inadequate access to water and 2.6 billion lack basic sanitation[2]. Meeting basic physical needs does not guarantee a good life either. In wealthy countries, up to 27% of individuals can suffer from mental diseases such as anxiety, mood and impulse-control disorders[3]. Depression-related diseases are projected to be the primary cause of death and disability by 2030[2].

An ever-growing economy requires continuous inputs of human time and effort, energy, minerals, land and water; and in turn sets the conditions for social and ecological crises. Environmental harm is often condoned; rationalized as the "unavoidable" consequence of human development. In fact, ecological degradation is one of the strongest barriers to need satisfaction, especially for the most vulnerable[1]. The benefits and harm of current so-called "development" strategies are heavily polarized. The wealthiest 10% of the world's population account for 50% of the global consumption emissions, while the poorest 50% are responsible for 10%[4].

Sustainable development means satisfying needs while enhancing nature and society. A prerequisite is to understand the interrelations between ecological and social well-being from a comprehensive conceptual approach and through reliable quantitative tools. The challenge of sustainability science is to demonstrate paths towards harmonious human-human and human-nature co-existence. Re-making societies of sustainable lifestyles requires science-based and socially-centered strategies that foster the values and goals of sufficiency, cooperation, intrinsic motivation, equity, etc. Consequently, the valid strategies (systems, practices, technologies) are only those effectively proven to satisfy human needs and enhance planetary health simultaneously.

1.1 From impact drivers to sustainability pathways

For half a century, the impact identity (IPAT) has influenced the mainstream understanding of drivers of the global environmental crisis[5]. According to the IPAT concept, environmental impact (***I***) is the product of population (***P***), affluence (***A***), and technology (***T***):

$$\boldsymbol{I = PAT} \qquad (1)$$

The popularity of the IPAT relationship lies in its simplicity as it implies a direct cause-effect relationship between variables. Although the IPAT equation is embedded in educational programs, policies and international development strategies[6], it is hardly useful as a meaningful accounting methodology[7], and even less to test hypotheses or visualize a full spectrum of solutions beyond the status-quo[8,9].

Moreover, a direct cause-effect thinking, endorsed by the IPAT lens, often confounds the concept of "drivers" (underlying causality) with the concept of "determinants" (associated factors) of impact[10,11]. As such, the IPAT view does not allow for questioning the current socio-economic paradigm as a driver itself. Nor its underpinning lock-ins, values, goals, and the (in)ability to change them[12,13].

Envisioning policy options beyond the IPAT range requires, at the least, dissecting its variables to explore the potentials of demographic shifts, alternative lifestyles, eco-efficient quality of life and grassroots initatives[14–17].

Table 1 summarizes phenomena within each of the IPAT variables that can influence the assumed linearity among technology, population, affluence and impact[18,19].

Table 1 | Examples of phenomena within variables of the IPAT equation. Traditional measures are contrasted with potential lifestyle factors for non-linearity or gaps between these variable and their impact. All of the "lifestyles gap explanations" are topics within this thesis.

Variable	Traditional measures	Lifestyle gap explanations (Tier 2 drivers)	Examples
Population	Size (number of inhabitants)	Demography: age, sex, fertility rate, migration Anthropometry: weight, height, Body Mass Index. Bio-demography: longevity, ageing Human energy: caloric demand, activity level, basal metabolic rate	The population pyramid, distributed by age and sex, directly determines the minimum endo-somatic energy (food requirements) and indirectly the exo-somatic energy (fuel requirements) as lifestyles and needs evolve with the human life cycle[20].
Affluence	Income or consumption (EUR/cap)	Intangible factors: Values, norms, motivations, well-being, capabilities and human needs. Tangible factors: Size of family, income quintiles, weather, diet, rural/urban , education, dwelling size, geography, energy and other infrastructure, etc.	Two persons with the same income might spend differently. Two persons with similar expenditure might spend in very different goods. Two persons with same material consumption might have very different life satisfaction[21].
Technology	Intensity of technology use. (CO_2/EUR)	User behavior i.e. gap between the "product efficiency" and "service efficiency" that it delivers[22,23]. Owning technology locks-in other resources (e.g., durable goods). Household production/prosumers. The environmental intensity and elasticity of the economic good being purchased.	Energy efficiency driven by end-user behavior[24]. A house is designed to require X amount of kWh/m2 of space heating, but the user preferences and occupancy drives impact (kWh/cap-yr). A vehicles' fuel efficiency (L/km) is driven by the number of passengers (L/passenger-km)
Impact	Emissions or resources per country, per capita, per product. (CO_2/cap)	The actual impact depends on the fragility of the ecosystem where it occurs, the vulnerability of the people exposed, the scarcity or criticality of a given resource.	Emitting X amount of particulate matter in Beijing is more detrimental to people's health as if emitted in Oslo. Due to the poor air quality and social vulnerability that hinders mitigation. Same pollutions level affects more a baby than an adult.

1.1 Fundamental human needs: sustainability at a human scale

Popular wisdom says we care about what we measure, and measure what we care about. Development strategies focused on fundamental human needs imply a radically different epistemology towards sustainability and well-being (
Figure ***3***). First, **satisfying human needs is the ultimate driver of all human endeavors**. Second, environmental impact is the result of the strategies employed to satisfy needs [21,25].

Needs-centered strategies depart from diagnosing current levels of need satisfaction and stating desirable thresholds[15], while also considering the subjective public opinion (or satisfaction) with respect to current levels and future goals. Contrary to the assumptions that inputs (monetary or resources) contribute to quality of life, a needs approach addresses specific societal outcomes directly (
Figure ***3***)[21].

The next step is to link needs to their most efficient satisfiers and the types of capital that they require. In this way, societies can better judge the adequacy of the strategies and amount of capitals devoted to each need[15,26]. In other words, are the resources and strategies employed effectively contributing to need satisfaction or simply perpetuating economic inertia? Could we spare resources and enrich capitals by employing different strategies? Can we redirect resources to areas where they have proven societal benefits? Such a view broadens the operating space for options of change beyond the classic dogmas of "consume better, produce efficiently"[14,26].

For example, the need to *participate* and to *create* in a given community might require commuting in order to interact, work, engage with others, etc. Satisfiers can come in the shape of private or public vehicles, motorized or active transport, and resource-intensive or minimalistic infrastructures. Further, the choice of satisfier might exclusively address a specific need, or synergistically satisfy multiple needs. For example, urban design for cycling and walking might additionally enhance *freedom*, *leisure* and *protection* (safety and health)[25]. Clearly, strategies that address the same needs can have very different impacts on the various capitals in
Figure ***3***.

Policy frameworks and scientific approaches are evolving towards explicitly addressing multi-dimensional well-being[27,28]. Such a shift implies acknowledging the limitations of material resources to satisfy all needs, as well as the contribution of non-market and non-material factors for social well-being[27]. Further research could simultaneously model the relationships between different type of capitals[29–31], planetary boundaries[15] and represent social heterogeneity[1,11]. Such efforts lie beyond the scope of this work.

Here we explore frameworks and case studies towards bridging industrial ecology with other fields and with the interest of the general public. The purpose is to contribute new perspectives to reconcile social well-being with environmental sustainability.

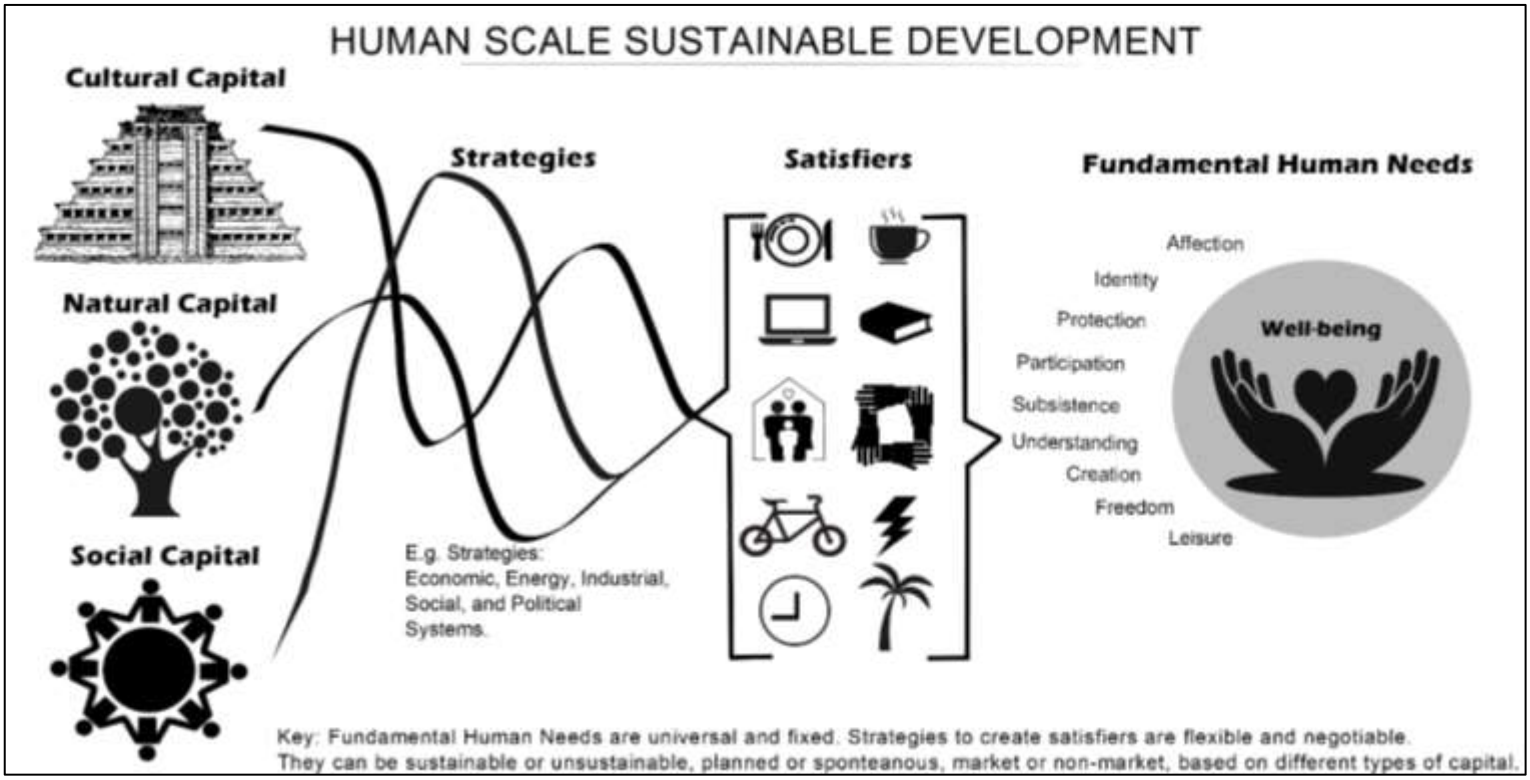


Figure 3 | Human Scale Sustainable Development. A framework based on Human Scale Sustainable Development would center on satisfying fundamental human needs by designing strategies of social metabolism that enrich all types of capital. Source: Own elaboration based on the taxonomy of needs described on Max-Neef's Human Scale Development[32] and Bourdieu forms of capital[33]. All icons are of free license (vecteezy.com).

1.2 Sustainable lifestyles: reconciling planetary and human well-being

Lifestyles are the dynamic "ways of life" people adopt according to their current psychological and socio-cultural traits such as world-views, identities, stages of life and goals. However, adopting certain ways of life is not solely a matter of choice. People need to overcome certain limitations[34] and require capabilities[35] to live the lifestyle they envision. Limited **personal resources** to adopt a desired lifestyle can include time, income, health and knowledge[36]. **External limitations** can be physical infrastructures (urban design, market offer) or social institutions (education system, economic systems)[14]. Social norms, culture and geographical context such as climate are **contextual variables** that moderate sustainable lifestyles[37]. All these factors, summarized in ***Figure 4***, shape mainstream lifestyles. The stronger the lock-in induced by the economic and provision systems[14], the less agency people have to "choose" their lifestyles according to their motivations, values and visions[14,38].

Studying lifestyles is affected by the observer (scientific discipline), measurement tool (method) and resolution of observation (scope of analysis macro/micro). Lifestyles are fluid as they relate to evolving characteristics such as age, economic status and social identity. At a collective level, age, sex and income distributions are fairly predictable and largely affect the outcomes for the future. Even the trajectories of how subjective values and beliefs change with modernization is relatively well-understood and arguably predictable[39]. In sum, lifestyle can be the result of factors as abstract as visions and world views and as concrete as the food we eat and goods we purchase (***Figure 4***).

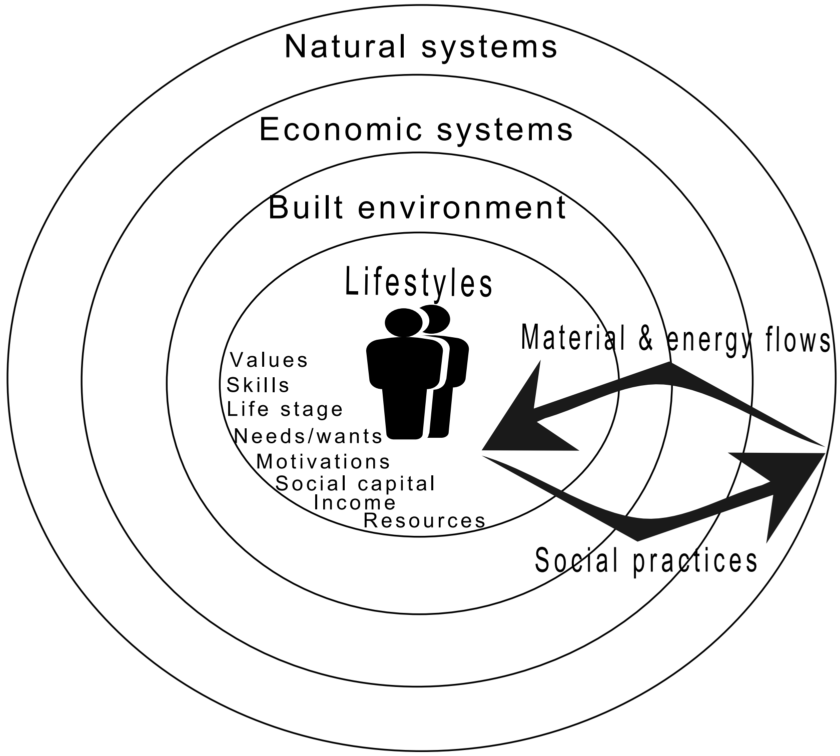


Figure 4 | Multiple levels and factors that influence lifestyles. Material and energy flows and social practices interact and regulate each other across all these levels.

Sustainable lifestyles can be more straightforwardly defined as: "a good life within earth's limits"[40]. The sustainable lifestyle concept derives from recognizing that the human impact on the planet is not only determined by the number of people, but mostly by how they live and satisfy needs. Specifically, by the amount and type of flows and stocks of materials and energy required by different ways of life [41]. As shown in ***Figure 4***, there are many factors beyond the agency of individuals that influence lifestyles such as institutions, infrastructures, social systems, etc. In practice, these factors also form part of what constitutes a sustainable lifestyle and should be designed to provide the most agency, while still being comprised purely of environmentally and socially beneficial options. Such considerations lie beyond the scope of this research. Here, we try to provide quantitative and analytical frameworks. Since sustainable lifestyles are multi-dimensional, an adequate framework to study them requires multiple indicators of well-being and environmental impact.

1.2.1 Bridging the gap between beliefs and behaviors

Environmental knowledge[42,43], attitudes[43,44] and even behaviors[45] are commonly used as proxies for sustainable lifestyles[42,44,45], but none of them guarantees reduced impact. Individuals seeking a sustainable lifestyle might be hindered by the dominant influence of socio-economic factors on consumption levels[44,46]. From a social practice theory, lifestyles are better understood by considering how behavior in one area of life interconnects with other life domains and people[47]. In this light, lifestyles are not simply a cumulus of behaviors, but they are also shaped by the practices and context reproduced by society[37].

Empirical evidence of the behavior-impact gap[45], rebound-effects[48] and spill-overs[49] show the importance of a comprehensive measure of impact associated with lifestyles, rather than looking at isolated behaviors. A behavior-impact gap might occur when individuals' efforts are limited to adopt convenient habits, but which have relatively small impact[42,44] (e.g., recycling). Further, the available voluntary lifestyle changes are often limited to consumption of less harmful goods (i.e. "green consumption")[50,51], and constrained by institutional, infrastructural and behavioral lock-ins[52,53].

The rebound effect and spill-overs are empirical evidence of the interconnections across different spheres of life. A spill-over occurs when a certain behavioral change in one domain of consumption leads to changes in other domains[54–56]. A rebound effect happens when a behavioral change leads to money savings and these savings are further spent on even more harmful products[48]. The prevalence of these phenomena suggests that to understand the environmental implications and the drivers of an individual's actions, one would need to capture the most environmentally relevant behaviors, regardless of their visibility.

1.2.1 A combined lifestyle – footprint - well-being approach

If we aspire to reap the potential of lifestyles changes, we must ensure that the proposed alternatives are indeed better for the environment and for people. Identifying **sustainable lifestyles** requires a metric to assess the environmental impact embedded in particular ways of living. Ideally, such a metric is based on environmental indicators that fully capture the global, life-cycle, impact of a lifestyle (e.g., carbon footprint) and with respect to a baseline of comparison (e.g., average citizen, time period, and environmental goals).

Since lifestyles are conformed by a pool of complex and interrelated behaviors and thus less "visible" than most of the behaviors studied in psychology, consumption footprints are a reasonable, quantitative, indicator of the environmental burden associated to a given way of life.

A footprint-lifestyle approach covering the most relevant consumption domains (housing, food, transport, etc.) is the minimum recommendation to address the limitations of purely behavioral studies[45].

A footprint metric is especially relevant in modernized or wealthy nations, which by and large drive global environmental impact[57], mainly due to the consumption of market goods[4,41]. Modernized lifestyles refers to individuals and households where market consumption largely drives environmental damage[4,41]. Depending on the baseline of comparison, a lifestyle can be sustainable in absolute or relative terms. A **lifestyle-footprint** approach can identify and cluster sustainable lifestyles under both, relative and absolute concepts of sustainable lifestyles [4].

1.2.1 Relative sustainable lifestyles (within group comparison)

A **relative sustainable lifestyle** is one which, when compared to its socio-economic counterpart, exhibits similar or higher well-being with lower environmental impact due to its choices of housing, transportation, diets and consumption in general. Alternatively, a lifestyle can be sustainable in reference to a past value or an environmental goal, e.g. if water consumption lies within water availability in a given area.

Many studies identify a sustainable lifestyle according to what an individual buys, when and why[58]. They seek to identify the characteristics of the green consumer. For example, researchers found that older, educated, high income females, with liberal orientations are more likely to engage in sustainable practices[56]. While interesting, such insights are not readily indicative of sustainability without a life-cycle footprint and a baseline of comparison.

1.2.2 Absolute sustainable lifestyles (planetary boundaries)

An **absolute sustainable lifestyle** would imply environmental footprints below planetary boundaries[59]. Tukker and colleagues define the global sustainable annual targets for carbon, water and land as annual footprints to be 2-2.5 t/cap, 150 m^3/cap and 0.01 km^2/cap[60], respectively. Thus, an **absolute sustainable lifestyle** is achieving well-being within planetary budgets[15].

The choice of scope and environmental indicator depends on the research question. A global perspective calls for consumption based accounting from a life cycle, multi-indicator and top-down approach[61,62]. In contrast, a focus on the local environment requires bottom up data of sources and sinks of pollution to complete the analysis.

Ideally, a footprint will also assess all the actions and transactions that occur off-market. Non-market behavior and informal economies are more relevant when studying the extreme poor, self-reliant, radicals (e.g., freegans, alternative currencies, eco-villagers), poachers (e.g., copper thieves) or urban hunters and gatherers[63]. Their behavior might have environmental relevance but occurs beyond the market and thus cannot be traced with current frameworks.

1.2.3 Different lenses on sustainable lifestyles

Sustainable lifestyles can be seen from at least three different perspectives[64]:

- Effectively, a lifestyle is sustainable when in effect allows the world's poor and future generations to meet their needs by being able to realize a decent quality of life, regardless of the intention behind the lifestyle. Such is the working definition of this thesis, based on quantitative data.
- Based on intention, one could consider only such behavior sustainable that is motivated by the wish to allow the world's poor and future generations to meet their needs and to realize a decent quality of life – rather independently of the behavioral effects.
- From a process perspective, sustainable lifestyles are lived in line with principles of sustainability, for example by establishing voting procedures on decisions concerning environmentally relevant infrastructure that are consistent with principles of inter- and intra-generational justice.

The concept of sustainable lifestyle carries the same ontological quandaries that make sustainability a 'wicked' problem[65]. It is impossible to know with certainty whether current practices compromise the ability of future generations or of deprived communities to satisfy their needs, as we cannot dictate the satisfiers they should rely upon. However, this "wicked" issue is less problematic when looking back at the framework for human scale sustainable development" in

Figure 3. In this light, the sustainability agenda can be reframed as "guaranteeing the freedom of deprived communities and future generations to self-determine strategies of need satisfaction". This concept might be clearer but it is also more challenging. It implies that the most prudent approach is to preserve intact and enrich the underlying natural, social and cultural capitals. It also implies avoiding development lock-ins that could hinder the self-determination of future societies[13].

1.3 Research gap and thesis contribution: Connecting human ecologies to industrial ecologies

1.3.1 PAPER I: Planetary and human well-being

The debate on what constitutes a good life and its relationship to material wealth has been central to religions, rulers and philosopher for milenia[66,67]. The interpretation of empirical evidence on this subject has been heavily polarized in the social sciences during the last half century[68]. The theory of well-being underlying a given policy or development agenda has tremendous implications for material resources. Some of the most influential schools of thought around well-being can be grouped in the following three categories:

Desire fulfillment theories, which conceptualize well-being as the satisfaction of revealed preferences. This is the underlying assumption behind mainstream economic theory[67].

Objective list theories, which attempt to catalog the goods required for a well-lived life. This is the *modus operandi* of development institutions such as the World Bank or the International Monetary Fund, which typically focus on "basic needs", i.e., equating needs to materials goods such as food, shelter and clothing[69]. Theoretical development within this approach has been largely shaped by the Capability approach, and the lists of components for well-being investigated by Amartya Sen[35]. Recent empirical reviews to operationalize the "objective lists" approach through an environmental lens has been undertaken by Rao and colleagues[70–72].

Hedonistic theories, which equates well-being as pleasurable mental states. The interest in this approach in relationship to material wealth was triggered in 1974 by the Easterlin Paradox, i.e. after a certain threshold, increasing economic growth does not correlate with increasing well-being[73,74]. This claim has faced strong opposition from Wolfers, Stevenson and Veenhoven who systematically find positive and long-term, although diminishing, relationships between well-being and wealth[75,76]. Remarkably, this enduring and expanding debate is based on a rather weak assumption, namely that subjective well-being is a reliable and useful indicator of human well-being. Despite the limitations of this indicator being pointed out by its own creators, subjective well-being is not a guarantee of mental nor emotional health[77], nor a guarantee of satisfied human needs[78]. More pragmatically, a hedonic view of well-being is not compatible with environmental mitigation strategies as it implies that reducing consumption affects well-being[67].

Eudemonic theories, which focus on the activities, abilities, or functionings (rather than goods) that constitute a good life. The concept dates back to Aristotle, but remarkable operationalization has been developed by Nussabaum, Sen[79,80] and Max-Neef[32]. A distinctive factor of the eudemonic approach is its multidimensionality of human well-being, as it combines physical, social and psychological needs.

PAPER I Contribution: Sustainable human scale development framework and evidence on the impact of need satisfaction

Costanza et al. integrate these schools of thought through a framework that is actionable at different scopes and fueled by multi-dimensional indicators[27]. This approach has been loosely applied by international organizations[28,81]. The challenge of applying this approach is to keep a balance between providing a broad framework to allow for self-determination and multi-cultural world views of what constitutes a good life, while ensuring enough specificity for it to be measurable[67]. In this sense, Max-Neef's distinction between needs and satisfiers resolves these issues in an elegant matter, which is why we chose it for our research.

Some recent empirical efforts connect needs to resources[22] and correlate societal progress with environmental boundaries[15]. However, none of these previous efforts have coupled fundamental needs to material resources in order to provide a quantifiable indicator of the impact associated with fundamental human needs. Further, there has not been a systematical evaluation of the subjective and objective outcomes associated with investing a certain amount of resources into fundamental human needs. In PAPER I we address both research gaps simultaneously as a proposal to approach human scale sustainable development (

Figure 3).

PAPER I demonstrates an option to assess society through a joint needs-based and disaggregated-consumption lens. In practice, this implies monitoring systems that combine multiple indicators to measure multi-dimensional environmental criteria, traceability of industrial systems and subjective, objective and values indicators of societal outcomes. In PAPER I, we demonstrate that the time is ripe to do so. The fundamental needs framework is key, because it allows for participatory decision making and democratization of sustainability, a topic explored in PAPER II.

1.3.2 PAPER II: Sustainability scenarios as a participatory process

Because sustainability is normative, someone has to explicitly define it. Defining it automatically sets goals, which in turn narrows down the potential pathways forward. What is sustainability and how should we get there? The answer might vary from a politician, to a scientist, technocrat, poor farmer, indigenous person, child or anarchist. Who should we ask? Ideally, everyone!

While scientists have the duty to connect the pieces of the sustainability puzzle, provide a comprehensive perspective and identify opportunities and risks; everyone has the right and responsibility to decide how to live and to steer society towards a better place. Steering can be done by bottom-up initiatives, benevolent governments, mass civil disobedience or by pressuring the powerful to take action[82]. In any case, steering efforts are ideally informed by scientific evidence. For science to be relevant to citizens, the results should speak to their demands. For this to happen organically, they would ideally co-create science.

Participatory modelling is one of the approaches to integrate citizens into sustainability research and agendas[83]. It is essential for participatory modeling to engage implicit and explicit knowledge of stakeholders to create formalized and shared representations of reality. Most systems sciences accommodate this principle, e.g., agent based modeling, system dynamics, network analysis, futurism and knowledge engineering. However, this is not commonly coupled to Industrial Ecology and input-output analysis (see Methods).

Participatory modelling can be seen as building human capital via social learning or knowledge co-production[38]. Its practice enriches scientific research, the participants and, if taken to its ultimate consequences, the general public, by leading to policies that truly consider the visions and needs of the citizens.

Contribution: Participatory modelling scenario framework and evidence of green consumption and sufficiency potentials

The popularity of environmental modeling with stakeholders has grown considerably in recent years. It has been spurred by the notion that including stakeholders and a wide variety of scientific perspectives is required to improve our understanding of social-ecological systems and current environmental problems. The challenge is to find a balance between a tool that is supportive and supported by stakeholders while providing compressive and transparent simulations of the implications of different pathways.

PAPER II contributes to this research gap by bridging the discipline of futurism and visioning with industrial ecology analysis. In particular, we use backcasting methodology to build consumption scenarios evaluated through multiregional input-output (MRIO) analysis. This is a fundamental step to add a life-cycle perspective to stakeholder inspired, and scientifically assessed, scenarios of sustainability. Involving citizens in public decision-making enhances empowerment and intrinsic motivation[84], which are prerequisites for sustained behavioral change[85]. Further, backcasting can point to individual[86,87] or social[88] co-benefits in quality of life that come with sustainable lifestyles, which may serve as policy leverage. In sum, backcasting is helpful to harmonize top-down agendas with the needs articulated by citizens[89].

However, mainstreaming this practice can be cumbersome as it is subject to time, knowledge and budget constraints. While some think that "community empowerment may not be possible without including technical experts as part of the constituency"[83], many citizens are already actively pushing for change, organized as grassroots initiatives. What are the potential effects of grassroots innovations that occur at the margins of political and scientific activity? This is the topic explored in PAPER III.

1.3.3 PAPER III: Sustainability grassroots initiatives as change agents

Demand-side solutions become more relevant as the sustainability community acknowledges that supply-side and technical change alone might fall short to achieve societal goals[9]. The upcoming Intergovernmental Panel on Climate Change assessment report will feature, for the first time, a chapter on demand-side solutions, focusing on the behavioral potential to mitigate climate change (Chapter 5, Working Group III, AR6)[9].

Sustainability oriented grassroots initiatives have been suggested to have potential for social transformation[14]. Similar to participatory modelling, grassroots initiatives aim to engage citizens, but in directly modifying current consumption practices. Initiatives such as the Global Ecovillage Network[90], the Transition Town movement[91], Repair Cafés[92], fossil fuel divestment[93], food cooperatives[94], etc. have gained traction, upscaling both in terms of engagement and geographical coverage, going from dozens to thousands initiatives during the past decades.

Despite their traction and potential, they are not seriously considered within the spectrum of demand-side options to mitigate climate change and enhance well-being, both of which are critical issues of our time. One of the reasons is the lack of clear scientific evidence. Namely, there are not enough systematic quantitative assessments supporting previous qualitative research on the role of grassroots initiatives for social learning of sustainable behaviors[95].

Contribution: Self-reported life-cycle carbon footprint and evidence of double dividends in grassroots activists

PAPER III contributes to this literature gap through a quantitative assessment on the role of grassroots initiatives for transformation. We find grassroots initiatives interesting for their capacity to amalgamate environmental stewardship, community-based action, individual behaviors and well-being.

At the same time, PAPER III provides a tool for calculating a life-cycle carbon footprint based on a minimum bundle of survey questions. This methodological contribution is non-trivial, as overlooking the behavior-impact gap is one of the main reasons that lifestyles potentials detected by social scientists via behavioral proxies are not reliable[45]. By presenting our methodology, we hope to encourage and enable the social science community to adopt life-cycle and global perspective in assessments of behavioral potential for mitigation.

However, this footprint assessment tool falls short of capturing the stock of household durables. The reason is that durables do not appear to be of paramount importance for household impact when looking at yearly footprints[41]. Methodologically, they are diverse and would require a large portion of a survey in order to assess. We hypothesize that the practice of owning household durables, might not only require significantly complementary resources directly and indirectly, but they also affect lifestyle choices[96]. For this reason, in PAPER IV we explored the role of durable goods and their complementary operating energy, goods and services for household impact.

1.3.4 PAPER IV: Durable goods: well-being or lock-in?

There is an inherent relationship between material stocks accumulated as infrastructures and machinery and the flows needed to build, maintain and operate such stocks [97]. Household durables can be seen as stocks that foster long-term path-dependencies due to their physical longevity and the social practices that they accommodate[98].

On one hand, a minimum level of durables is fundamental for the well-being of individuals and the development of nations[72,99]. On the other owning a large bill of durable goods might accommodate a wasteful consumption of energy[100,101]. Higher income households in both emerging and advanced economies tend to own more durable goods [102–104]. By 2050, the number of electronic devices is expected to increase by 80% in the global North, to 42 devices per capita and almost by a factor of 3 in the global South, to 24 devices per capita [105].

Because durable goods are not purchased frequently and are not particularly carbon intensive, they appear to have a modest role for climate change[11]. Our hypothesis is that durable goods have an underappreciated role in shaping the overall energy needs, not only due to raising operational energy requirements, but also due to the energy embodied in complementary consumables and services that they demand. The acquisition of durables has many linked energy requirements, which have not been examined together.

Contribution: Durables-centered framework and evidence on their energy lock-ins

PAPER IV adds to previous literature by reporting households' final energy footprints embodied in goods according to their functionality and durability (e.g. durable goods, consumables and services). We slice energy demand into durables and non-durables as a step towards aligning sustainability strategies with consumer options and lifestyle lock-ins[106].

The paper contributes to the understanding of stock-flow relations within households and the implications for economic and energetic poverty alleviation as well as sustainable lifestyles. We do this by showing that durable-related consumption drives around two-thirds of households' energy footprints.

Further, the observed relationships presented in this paper will potentially extend into the near future, given the lifespans of current household technologies in place, and the infrastructure and lifestyles lock-ins that come with them. The paper raises awareness in the policy and resource modelling communities to explicitly address the inertia driven by durables and related goods.

1.3.5 PAPERS V, A & B: Impact heterogeneity

Targeted policies are often more effective than general policies. However, targeted policies are supported by research that differentiates the needs of different population segments e.g., geographical locations, age cohorts, socio-economic groups, etc[1]. PAPER V and additional papers A and B make contributions in the general of direction of improved household heterogeneity.

Contribution: demographic and bio-physical heterogeneity

PAPER V joins demographic research with the type-cohort-time approach typically applied in dynamic material flow analysis[107]. This article shows the bias in treating populations' biophysical characteristics as homogenous across nations and static. This paper also fills a methodological gap by showing how to apply demographic models to industrial ecology assessments towards improved resolution, differentiated needs and better understanding of the drive and fate of resources.

Contribution: Sub-national geospatial and socio-economic heterogeneity

PAPER A maps the heterogeneity of impacts within European countries and tests the influence of several socio-economic factors on consumption. This research contributed to a better understanding of the hot-spots within nations in order to focus and differentiate mitigation efforts[11].

Contribution: household, behavioral and consumption heterogeneity

PAPER B adds to the gap by studying individuals and testing the role of specific consumption domains. It looks into specific lifestyles choices and shows the diversity of socio-economic and demographic factors that influence household environmental impact[96].

1.4 Summary of research objectives and questions

The broad motivation of this research is to contribute to the elucidation of what is perhaps the most significant global problem of our time: the interplay between development, natural resources and well-being.

The goal of this project is to transcend the standard application of industrial ecology tools to other fields and through a social perspective. The broad research questions are summarized as follows:

1. What is the environmental impact associated with fundamental human needs and their satisfaction? **PAPER I**
2. What are the environmental consequences of stakeholders' visions of sustainable lifestyles and their implications for well-being? How can we integrate participatory modelling into MRIO analysis? **PAPER II**
3. Are bottom-up grassroots initiatives an option for lower impact and higher well-being? **PAPER III**
4. What are the lock-ins associated with modern lifestyles that rely on durable goods? What does it mean for sustainable lifestyles? **PAPER IV**
5. What is the level of heterogeneity across populations and what does it mean for sustainability? **PAPER V, additional papers A and B.**
6. How can industrial ecology tools be applied to study sustainable lifestyles from multiple perspectives and through combined research methods? **THESIS**

2. Methodological approach: One size fits none

2.1 Research epistemology grounded in systems thinking

Human-nature relationships can be studied from multiple systems sciences of varying breadth. A discussion of each field and the methods they encompass lies beyond the scope of this work. Nevertheless a brief set of definitions can suffice to clarify our research epistemology and to situate industrial ecology, which is the main tool-kit used in this thesis, within the systems perspective philosophy and subsidiary disciplines:

Systems Perspective: "Understanding of a system by examining the linkages and interactions between the components that comprise the entirety of that defined system."[108]

Human Ecology: "Human Ecology is the study of our relationship among communities and in relation to their environment."[109]

Socio-Economic Metabolism: "The material input, processing and releases of societies and the corresponding energy turnover."[110]

Industrial Ecology: "Industrial ecology is the network of all industrial processes as they may interact with each other and live off each other, not only in the economic sense, but also in the sense of direct use of each other's material and energy wastes and products." [111]

Figure 5 summarizes the relevant disciplines and their relationship to each other in terms of scope. Systems thinking is often regarded as a broad agglomeration of ideas from diverse intellectual traditions and thus encompasses all other systems disciplines. Human ecology, socio-economic metabolism and industrial ecology all follow a systems perspective approach. In other words, industrial ecology is a systems perspective discipline but systems perspectives is not an industrial ecology discipline. The differences between them is indicated by the breadth of their scope with respect to human systems i.e. their system boundaries. Industrial ecology and socio-economic metabolism are both concerned with physical flows, but industrial ecology focus on techno-economic systems and therefore is limited to the formal economy while socio-economic metabolism is broader, as it looks at society beyond markets. Human ecology is more broadly concerned with human-human and human-environment relationships as "environment" includes both built and natural ecosystems.

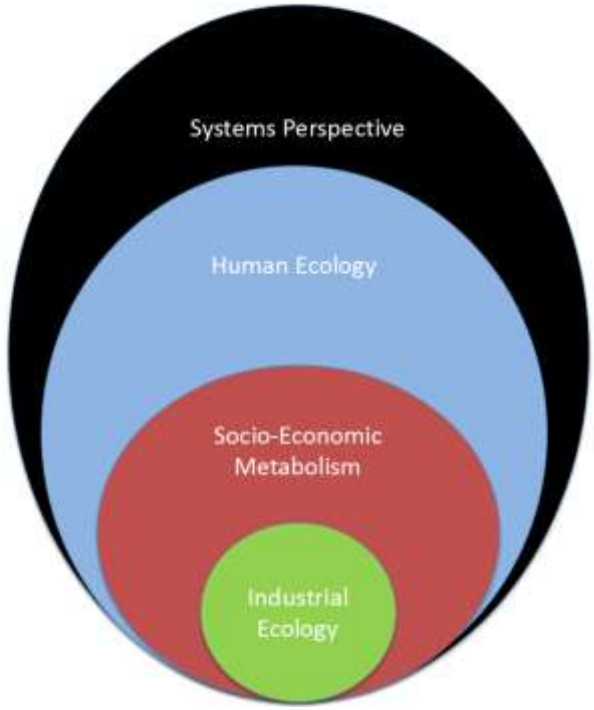


Figure 5 | Systems disciplines concerned with human-environment relationships. The oval size indicates the scope. Key: “Systems perspective” is the broadest in scope and thus includes the rest of disciplines.

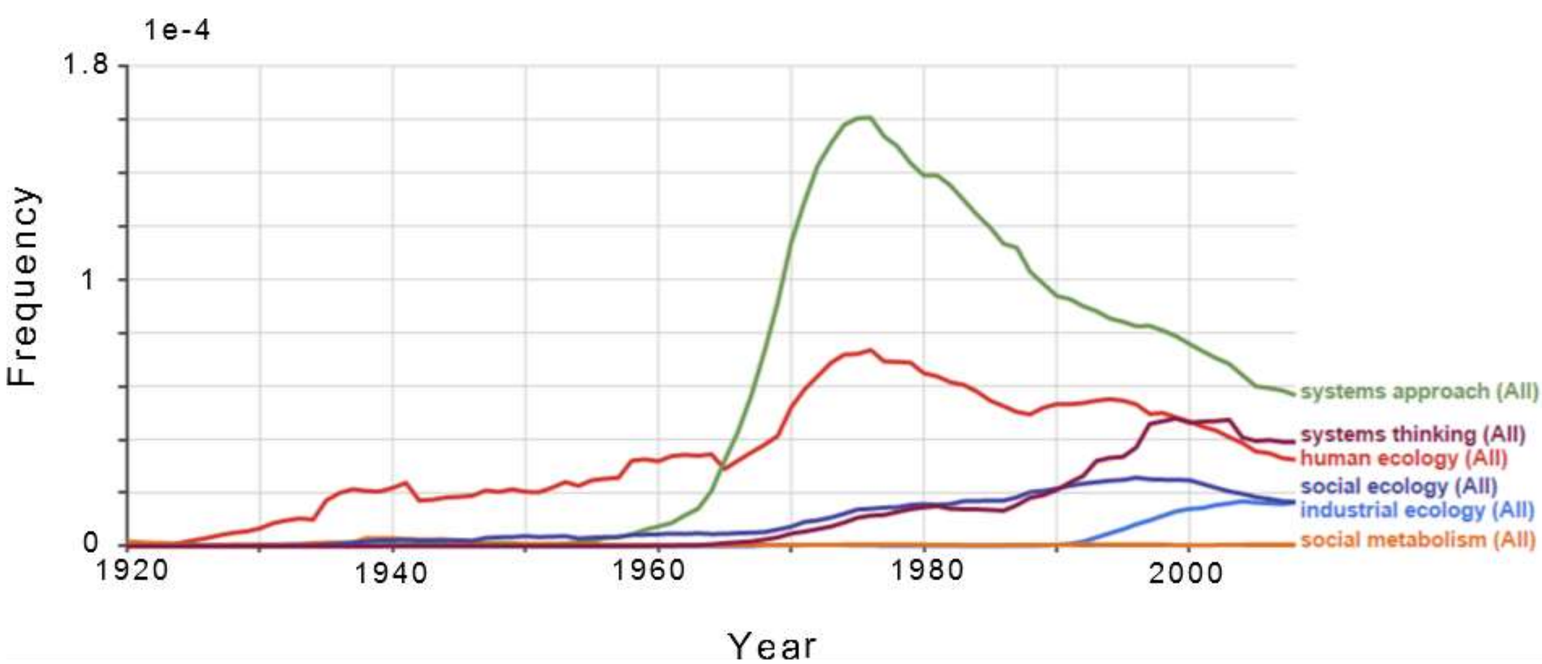


Figure 6 | Usage frequency of the selected terms. Pulled from the corpus of books written in English between 1900-2008 (x-axis), generated with Google Ngram following the Cultormics approach[113,114].

Approximate sample size of 4 million books. Only matches found in at least 40 books are reported. The chosen terms are the result of testing possible wording variants and versions of the concepts. Usage frequency is computed by dividing the number of instances of the n-gram in a given year by the total number of words in the corpus in that year.

Figure 6 presents a bibliometric analysis of the relative popularity and interest of each term over the last century. It is interesting to note that all these terms were virtually absent in printed books before the 20th century. The use of broader "systems" terminology precedes the more disciplinary, method-oriented approaches, with industrial ecology rising only after 1990. The precise beginning of the systems field is a matter of perspective. Arguably the roots of systems thinking precede the academic terminology, reaching back to ancient Western and Eastern philosophies (and –ers) including the Mayans, Shamanism, Sufism, Hermeticism, Pythagoras and Lao Tsu[66].

Among the systems disciplines, industrial ecology stands out for its explicit social commitment, which align well with the motivation of this thesis:

> "Inform purposive human decision making about industrial production processes, especially as they impact the environment, by taking advantage of knowledge about the functioning of successful ecosystems."[112]
>
> "Improving the environmental compatibility of individual industrial processes is evaluated in the context of improving the overall industrial system"[112]

2.2 Industrial Ecology Methods and Data: Linking Systems

As mentioned earlier, the motivation of this research is to better understand the complexity and inter-connectedness of the world's needs and resources. We chose an industrial ecology tool-kit, centered on multi-regional input-output analysis, due to its particular strength at linking industrial, economic and natural systems[115]. Further, we explain the motivation of our methodological choices to address our research motivation.

Global economic systems and production chains are increasingly technological, globalized and complex[116]. Characterizing their role in social metabolism and global impacts requires a broader scope and deeper detail than what traditional impact assessment tools offer[117]. Globalized supply chains imply a spatial disconnection between the places where natural resources are extracted, processed, consumed and discarded. Such a disconnection obscures geo-political issues of unequal trade as well as opportunities for international cooperation to lower overall impact[118]. Tele-connecting extraction with consumption calls for the explicit modeling of supply chains, embedding data on economic flows, bilateral trade and industry-specific requirements and outputs[119].

Furthermore, coupling economic flows with environmental impacts calls for a life-cycle perspective that accounts for resources' origins and fates[116]. Since current environmental challenges span beyond climate change, modelling energy, materials, water, land, and toxicity is also relevant for sustainability[15]. Thus, a "footprint family", composed of multiple indicators or footprints, should be jointly considered to capture nexus and synergies across impacts.

Because lifestyles span several consumption domains, the chosen research method would ideally have the resolution to differentiate between housing, food, transport, durables, services, etc., which is a fundamental step towards identifying the environmental implications of needs and choices.

Finally, modeling multiple relevant stakeholders is crucial to delegate responsibilities, clarify roles and detect footprint displacements across demand agents or nations. All the aforementioned issues and desired characteristics are addressed, to a large extent, by applying environmentally extended multiregional input-output analysis to calculate consumption-based environmental footprints. We base the core of this research on EXIOBASE, a state of the art model of the global economy and resources, which is open access and currently provides the most product detail[120], as described below. Across the articles, footprints of energy, carbon, land, water and human toxicity are calculated to analyze the impacts of consumption by households, governments and individuals.

While our core method is environmentally extended multi regional input output (EE-MRIO), we combined other tools and methods from environmental systems thinking and industrial ecology. life cycle assessment, dynamic material flow analysis were applied when relevant. Common statistical methods such as regression techniques were also used for result analysis.

2.2.1 Environmentally Extended Multiregional Input-Output Footprints

Consumption-based accounting attributes all production-based emissions and resources to the final goods produced in the economy[62]. In this sense, the impact of a nation equals the impact occurring directly by final demand agents (e.g., households, governments, etc.) plus the embodied impact from all purchased goods, including imports and excluding exports. We use the standard Leontief model to calculate final energy footprints of households[7].

$$\boldsymbol{x} = (\boldsymbol{I} - \boldsymbol{A})^{-1}\mathbf{y}_h \qquad (1)$$

Where x represents the total economic output of all sectors induced by a given final household demand $\mathbf{y}_h$ of the consuming nation, **I** is the identity matrix, and **A** is the technical coefficient matrix, representing the inter-industry requirements. (**I**-**A**)$^{-1}$ denotes the so-called Leontief Inverse **L**, the matrix of total requirements. The footprints are calculated as follows:

$$\boldsymbol{FP} = \mathbf{s}\,(\mathbf{I} - \mathbf{A})^{-1}\,\mathbf{y}_h + \boldsymbol{F}_{hh} \qquad (2)$$

Where $\boldsymbol{s}$ is the stressor coefficient vector resulting by dividing the a given factor of production or pollutant used or produced by a given sector by its economic output (i.e., TJ/EUR). $\boldsymbol{F_{hh}}$ represents direct operational energy used by households' electricity, transport, heating and cooking fuels.

The footprint calculations in this thesis are mainly based on EXIOBASE, an environmentally extended multiregional input-output (EE-MRIO)[120]. EXIOBASE3 includes accounts of the economic activity and trade for the world from 1995 to 201[121]. It includes 200 economic goods and services and 163 industrial sectors for each country. According to the research question, we consider the final demand of different economic agents (households, governments, non-profits) to calculate the consumption-based accounting footprints of goods and services in a given country[7]. EXIOBASE covers the 44 largest economies, which encompass about 91% of global GDP and 65% of the world population. The rest of the countries are aggregated into five "Rest of the World" regions representing the remaining countries in Middle East, Latin America, Europe, Asia-Pacific and Africa [122].

2.2.2 Physical Lifecycle Assessments

In addition, physical stressor coefficients (***s***) were derived from lifecycle assessment studies with the purpose of increasing the precision of our footprint models. The MRIO approach yields stressors expressed as physical per monetary units, which have limited application to micro-data or refined scenarios of alternative consumption due to aggregation and price effect issues. For example, all fruits and vegetables are aggregated within the same product. Similarly, the footprint is dependent on expenditure, whereas the same expenditure might purchase very different quantities, depending on the quality and price[123].

Product-specific lifecycle assessments which report physical stressors allow for differentiating products, thereby counteracting some of the limitations of monetary multipliers. For example, the impact of specific food products can be given per weight as CO_2/kg of edible produce or per kcal of product. Such an approach was especially relevant to add robustness to micro-data and scenario analysis of PAPERS II, III, and B, as documented in their respective Supplementary Information.

Combining physical lifecycle assessment information was especially relevant for the sectors of food, household energy and transport. We determined the carbon intensities of food items through literature reviews and standardizing results in kgCO2eq/kg edible product. 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 based on lifecycle assessment studies and Eco-invent 2.2[124]. We derive climate impact of electricity was using country-specific carbon intensities from Eco-Invent 2.2[124]. In PAPERS III and B, we modelled household physical energy demand using the Intelligent Energy Europe project TABULA[125], which collects and compares data of buildings representative of the national building stock in Europe.

2.2.3 Applying Dynamic Material Flow Analysis to Human Populations

PAPER V combines concepts from nutritional health sciences, demography, bio-demography, and dynamic material flow analysis, to deconstruct the role of population changes for food demand. The methodical approach is builds on the theory of demographic metabolism, introduced by Lutz[126] to explain how societal changes result from the changing compositions of the population and its characteristics (e.g. sex, age, life expectancy, educational level, etc.). Some of these characteristics might change over the life of a person (e.g. educational level, age, body size) or generations (e.g. life expectancy, anthropometric features). PAPER V takes advantage of the high granularity of open access demographic and health data.

The mathematical foundations for PAPER V are based on a "type-cohort-time" approach, which is typically used to model resource use in dynamic stocks of the built environment[107,127,128]. PAPER V describes how to apply a type-cohort-time approach to investigate the changes in resource (food) demand due to changes in the demographic structure and in the biophysical characteristics of the world's population over time.

Combing all these approaches is useful to address bottom-up human needs or to model the underlying dynamics of the population as a driver of resource use. In PAPER V, we regard population as a dynamic stock constituted by individual elements of diverse types, whose size and characteristics change in time - across generations or during the life course, and involving height, weight, life expectancy and metabolic rate, among other traits (***Table 1***).

2.2.4 Bridging industrial ecology tools with social sciences

Bringing together social, technical and natural systems lies at the juncture of physical, social and economic sciences. Naturally, a complex topic such as sustainable lifestyles and well-being cannot be tackled with one single method. Diverse realities across and within nations call for transdisciplinary, multi-level approaches. Depending on the scope, footprint calculations may quantify the impacts associated with consumption of individuals, collective action, households, communities or nations, as shown in Figure 7.

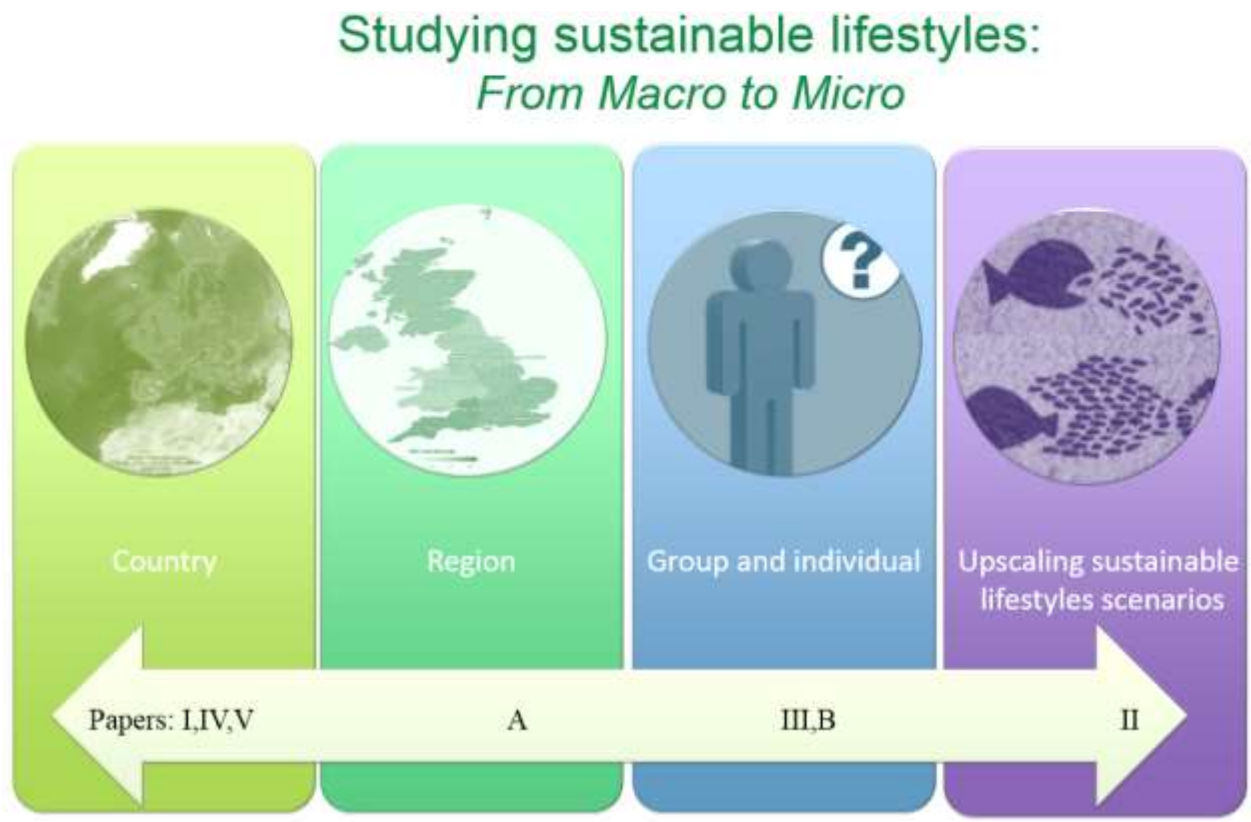


Figure 7 | Multiple scopes covered in this thesis to study sustainable lifestyles.

Multiple and mixed methods research can inform robust policies to consider the connections between scales and intervene at the adequate leverage points[129]. Beyond industrial ecology, we combined methods from participatory modelling, welfare economics, positive psychology, development studies, grassroots and transition science, stock-flow theories, bottom-up energy modeling, econometrics and economic theory. The main tools and methods from these disciplines that were employed in junction with EE-MRIO are discussed briefly below for each paper; more detail can be found in the papers themselves.

2.2.1 Methods Summary: Mixed methods through a systems perspective

Paper I combines EE-MRIO with an integrative approach to quality of life[27] and multi-dimensional perspective on human development[28,130]. The human scale development framework and taxonomy of fundamental human needs applied in this paper combine psychological insights on eudemonic well-being[131] and agency[38], with social psychology and welfare economics[25,132].

Paper II extends EE-MRIO by modelling physical layers on energy and food. Energy content was obtained from the International Energy Agency statistics on energy carriers[133] and caloric content from the Food and Agriculture Organization for caloric content in food products. Stakeholder workshops of backcasting visions for sustainable lifestyles and text coding was the basis to build the scenarios of sufficiency and green consumption.

Further, participatory modelling was applied through a backcasting methodology in order to build future scenarios of sustainable lifestyles. Backcasting is a participatory process that facilitates sustainable development by considering citizens in decision making[134 89,135]. It literally means "looking back from the future", and the procedure consists of collectively envisioning a desirable future and imagining the pathways forward[136]. Details about the backcasting methodology underlying this research can be found in the documentation of the GLAMURS project[135,137,138].

Paper III and B combine EE-MRIO assessments with other assessments of environmental impact to establish the consumption domains to be covered by the survey. Besides EE-MRIO multipliers, life cycle assessments, dietary surveys and thermodynamic modelling for space heating were needed to establish a comprehensive carbon calculator for self-reported behaviors and housing status. Insights from social survey design and behavioral sciences were considered for this article. Positive psychology and measures of life-satisfaction are also integrated. Research on grassroots initiatives from transition theory and innovation was also considered to strengthen our research approach[95,139].

Paper IV is mainly based on EE-MRIO and EXIOBASE3. Information on lifetimes of durable goods is based on material flow and stock accounting definitions on lifetimes, according to the LiVES database[140]. The paper is inspired by the classical stock-flow approach to the socio-economic metabolism of material and energy flows[97].

Paper V combines concepts from nutritional health sciences, socio-demography, bio-demography and dynamic stock-cohort modeling traditionally used within material flow analysis, but in this case applied to demography and population dynamics.

3. Summary and outlook

3.1 Research findings and conclusions

What is the connection between global emissions and satisfying human needs?

PAPER I deconstructs quality of life, and applies the fundamental human needs framework developed by Max-Neef et al. to calculate the carbon and energy footprints of *subsistence*, *protection*, *creation*, *freedom*, *leisure*, *identity*, *understanding* and *participation.*

We find that half of global carbon emissions are driven by *subsistence* and *protection.* A similar amount is due to *freedom*, *identity*, *creation* and *leisure* together, whereas *understanding* and *participation* jointly account for less than 4% of global emissions. We use 35 objective and subjective indicators to evaluate human needs satisfaction and their associated carbon footprints across nations. We find that the relationship between quality of life and environmental impact is more complex than previously identified through aggregated or single indicators. Satisfying needs such as *protection*, *identity* and *leisure* is generally not correlated with their corresponding footprints. In contrast, the likelihood of satisfying needs for *understanding*, *creation*, *participation* and *freedom*, increases steeply when moving from low to moderate emissions, and then stagnates. Most objective indicators of a given need show a threshold trend with respect to footprints, but most subjective indicators show no relationship, except for *freedom* and *creation.* Our study signals the importance of considering both subjective and objective satisfaction to assess quality of life-impact relationships at the needs level. In this way, resources could be strategically invested where they strongly relate to social outcomes, and spared where non-consumption satisfiers could be more effective.

What is the environmental mitigation potential of sustainable lifestyles envisioned by stakeholders in Europe?

PAPER II involved backcasting workshops to compile stakeholders' visions of sustainable lifestyles in Europe. We translate those visions into 19 scenarios of sufficiency and 17 of green consumption. We applied input-output analysis to estimate the scenarios' implications for land, water, carbon and human toxicity to explore synergies and trade-offs across footprints. We considered issues of global justice by tracing the share of impacts in foreign countries due to European consumption.

Reducing net consumption by working from home and commuting actively, local and peer-to-peer services, durable fashion, and reducing food surplus and waste are sufficiency options with significant mitigation potential. We find potential in shifting current expenditure towards green consumption options such as renting, sharing and repairing manufactured products, adopting passive house standards and eating plant-based diets. Beyond evaluating scenarios, we present a framework to integrate participatory modeling (citizens' visions) into comprehensive sustainability quantitative modelling. Understanding the global consequences of local collective action is key to direct society-wide efforts towards genuine sustainable living.

What is the potential of grassroots initiatives for reconciling social and environmental well-being?

PAPER III compares the individual carbon footprints and life satisfaction of grassroots initiative members with non-members sampled from the same geographical region (sample size = 1476 individuals). We further compare the groups by testing the influence of socio-economic variables that are typically associated with both footprint[46,141,142] and well-being[17,143]. We studied the carbon footprints of 141 members of 12 sustainability-focused grassroots initiatives located in Italy, Germany, Romania and Spain, spanning from food and clothing cooperatives, eco-villages and the Transition Town Movement.

We find that grassroots initiative members have 43% and 86% lower carbon footprints for food and clothing respectively compared to their regional socio-demographic counterparts. We find greater active travel distance and lower indoor temperatures for initiative members, yet no significant differences in the carbon footprint of housing and transport. Interestingly, increases in income are not associated with increases in the total carbon footprint of members, while the influence of income is confirmed for the carbon footprint of the total sample. Instead, factors such as age, household size, and gender better explain the variation in the domain-specific carbon footprints of initiative members. Finally, members show higher life satisfaction compared to non-members and are 11-13% more likely to evaluate their life positively. Our results suggest that initiative members uncover lifestyle features that not only enable lower emissions, but also decouple emissions from income and well-being.

What are the energy resources associated to household durables goods?

PAPER IV presents a resource and economy wide analysis of the energy resources associated directly and indirectly to durable goods. Sustainable production and consumption agendas push for high quality, long lasting goods. Durable goods, however, often require substantial amounts of energy in complementary short-lived goods and services. We calculate the life cycle energy footprints of 200 goods across the 44 largest economies and five world regions from 1995-2011.

We find durable goods to be responsible for 10% of the global final energy embodied in household consumption. However, the services and consumables complementary to durables amount to 8% of global final energy footprints, while the fuels and electricity to operate durables amounts to 51%. Thus, 68% of the global household final energy is associated with durable goods. The effect of wealth is more drastic for the marginal increases in the energy footprints of transition economies. The most intensive durables and complementary services relate to transport, dwellings and appliances, but require 6-25 times more per capita energy in advanced economies than in emerging economies.

While rising living standards invariably depends upon a bundle of durable goods, durables lock-in a higher energy throughput associated to their operation. The transition towards sustainable development relies on understanding of stock-flow relations within households. In this paper, we present wider perspective on durables as a step forward.

What is the impact of a populations' demographic and bio-physical changes on food resources?

PAPER V applies dynamic stock modelling to investigate the changes in food-energy demand due to changes in the demographic structure and in the biophysical characteristics of the world's adult population between 1975 and 2014. The population stock is differentiated by sex and cohort, and the body mass index and height are used to estimate the caloric demand of individuals according to their sex and age.

Today's average human is 14% heavier, 1.3% taller, 6.2% older, and 6.1% more energy demanding than their counterpart in 1975. Global food energy requirements increased by 129% over the past four decades. Population growth accounted for 116% of this increment, weight and height gains for 15%, and the aging phenomenon counteracted demand by -2%. This net additional 13% demand corresponded to the needs of 286 million adults, which is overlooked when assuming a homogenous and static food energy demand.

The effects of increased human mass were greater for some countries, where the weight of individuals increased by 33% in only 4 decades, corresponding to a per capita food energy increase of 16%. The results depict an additional burden to future food security beyond the mere growth in population, particularly because there is a trend towards body mass increases in most parts of the world. Using a demographically explicit stock-dynamics approach to population for addressing food issues goes beyond food security and could potentially explore resources in transport, clothing, household chemicals, sewage services, furniture, etc., associated with the collective effect of changing human bodies

3.2 General conclusions

This thesis explored the environmental and social implications of different human needs (paper I), sustainable lifestyle scenarios (paper II), grassroots initiatives (paper III), durable goods (paper IV) and population dynamics (paper V).

We present a variety of new perspectives on the human dimension of environmental impacts. Further, every paper in this thesis is discussed in the light of current and future pathways to raise living standards and enrich quality of life in a sustainable manner. The conclusions center on the potential of alternative consumption and bottom-up options, in an effort to contribute to the under-exploited policy domain of demand-side strategies.

This thesis work has global implications, regardless of the particular development status of nations. Emerging nations are bound to follow the unsustainable trajectories of wealthy nations [119,144]. However, since their systems are not fully deployed, they also have a golden opportunity to prevent the modernization inertia and develop differently to attain high well-being at a fraction of the environmental impact[145]. By contrast, wealthy nations have the challenge to reduce their bill of resources without compromising their well-being. Both cases require essentially the same approach: one that puts human needs in the center and encourages sustainable lifestyles across all spheres. This thesis contributes frameworks, tools, and empirical insights to this effort.

The broader conclusions for research and policies on sustainable lifestyles can be summarized as follows:

> **Disaggregate human needs and resources**. Different needs have very different resource implications and satisfaction outcomes. Consumption that is supposed to serve basic *protection* and *survival* needs drives the bulk of climate impacts but does not correlate proportionally with social progress in these areas. Similarly, different nationalities, age cohorts and body types have drastically different food requirements. These needs evolve with demographic transitions and are path-dependent on the historical food availability of specific countries. A needs centered view allows for sparing resources by focusing policies on providing a good life directly, instead of through economic or material proxies. However, a pre-requisite is to fully understand needs and measure their satisfaction adequately.
>
> **Involve stakeholders in sustainability science**. Large-scale lifestyle changes proposed by European citizens are a promising option to satisfy needs with less impact, with the additional

perk that citizens actually agree with such changes. Except for switching to plant-based diets, the lifestyles with most potential are those that imply curbing consumption towards sufficiency levels.

Evaluate across geographical scales. Cross-country analysis also reveals a full spectrum of consumption patterns and strategies to provide well-being. However, by looking only at individual micro data and groups, such as grassroots initiatives, we could conclude that the carbon footprints of activists are 15% lower than average citizens, while their life satisfaction is higher. Assessing multiple scales is key to differentiate responsibility, target specific groups and assess the role of socio-economic and infrastructural context. Heterogeneity in models is also a step towards harnessing the potential of stakeholders and of non-market options for transformation.

Apply interrelated and multiple indicators of impact. Beyond carbon, looking at other resources and impacts allows for identifying potential risks and synergies of different options. Sufficiency lifestyles entail fewer risk of trade-offs across footprints than green consumption options. While plant-based diets spare substantial land and water resources, replacing motorized transport with active modes yields larger reductions in carbon and toxicity.

Differentiate consumer goods by their material nature, functionality and the lock-in they represent. Different goods have very different implications for resources and well-being. Durable goods, for example, are associated with 6 times more impact when considering their complementary goods and energy. Considering all durable-related goods altogether, durables drive two-thirds of global energy resources. If owning long-lived durables shapes lifestyle choices, this has implications for our ability in the near future to curb consumption.

Assess beyond national territory and take responsibility for local consumption that drives impact abroad. Curbing European food and clothing consumption has the largest environmental benefits for the global South, while switching to better energy and transport offers most mitigation potential within Europe. Cooperation with trading partners to deploy cleaner production, fairer labor conditions, greener supply chains and more equal exchange is key to lower the impact of consumer goods and to take responsibility of a nations' impact abroad.

Differentiate stocks and flows to anticipate long term lock-ins. Both the energy lock-in the stock of durable goods as well as the energy locked-in into the growing body sizes of the global population indicate the sobering possibility that the relationships observed in this thesis are hard to break in the near future. The effect of past decisions with respect to stock accumulation compromises future resources. In this case, the cumulative effect of the energy demand and lifetimes of already existing household technologies and humans, and the lifestyles they lock-in, will likely span into the near future.

3.3 Limitations and Further work

The main limitations of this research are inherent to MRIO analysis. First, aggregation of goods into sectors and consumers into nations poses interpretation challenges. Better representations of heterogeneity in the technical systems call for more granular resolution of resource stocks and flows. Even if EXIOBASE is the open access MRIO with most sectorial detail today, finer product resolution is vital to model specific goods and their end-uses. Detailed data would allow for meaningful connections between goods, lifestyles choices and human needs. Improved heterogeneity in modelling social systems calls for disaggregating consumption at sub-national and individual level data. Although we conducted surveys to research individuals in PAPERS III and B, including more countries, lifestyles variables and consumption products would require coordinated international efforts. Open access global microdata that captures comprehensive information on lifestyles and granular resolution on consumption would allow for more meaningful socio-economic, well-being and time-use implications.

EXIOBASE allows for longitudinal and cross-sectional analysis of nations that belong to middle to high income groups. However, most low-income nations are aggregated into world regions. Deriving insights from cross-sectional analyses assumes "modernization pathways", the assumption that nations develop by following similar pathways, paved by economic and technological progress[101,144,146]. Although this assumption has been supported by longitudinal studies on societal transitions[39,101,147–149], some nations defy the paradigm by achieving high human development at a fraction of the resources required by wealthy nations[15,101,144,150]. Future meta-analysis could include more nations and test other environmental indicators such as materials, nutrients or metal footprints[15].

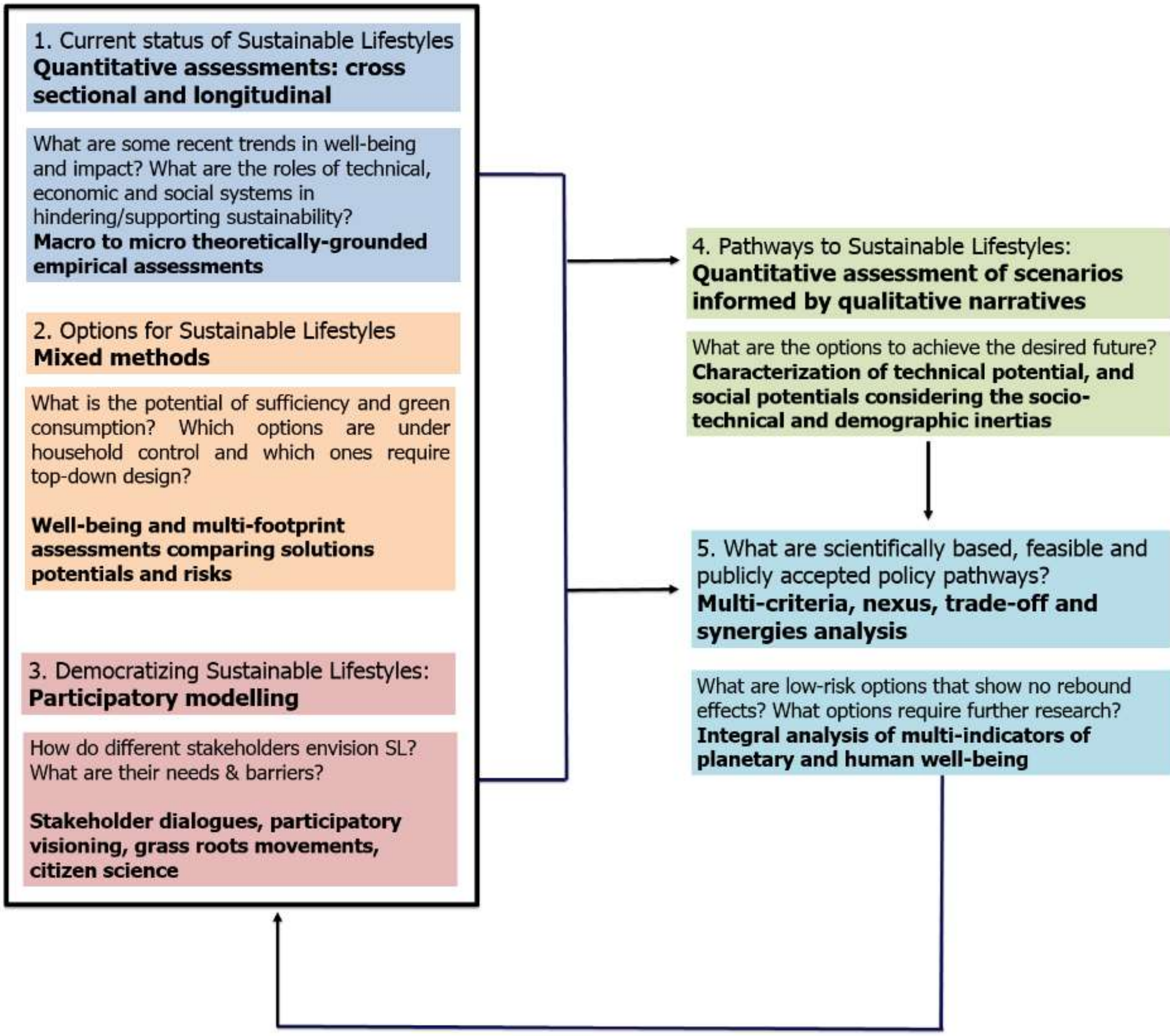
Second, MRIOs focuses on transactions within the market economy and non-market transfers by governments and Non-Profits Serving Households[120]. Especially in emerging and low-income nations, unpaid work and household production can be a significant sources of service provision and need satisfaction[25,151], with implications for time-use and well-being[72]. Even in high income nations, grassroots initiatives within the shared economy run on voluntary work, barter goods and provide services beyond the scope of current economic accounts[152]. Some of these initiatives have gained traction in the past decades, upscaling both in terms of engagement and of geographical coverage e.g., The Global Ecovillage Network[90], the Transition Town movement[91], Repair Cafés[92], fossil fuel divestment[93], food cooperatives[94], etc. For example, the Repair Café movement up-scaled from 1 to 1500 cafés world-wide in the past decade, currently repairing about 300,000 appliances per year globally[92,153,154]. This trend shows both the importance of considering grassroots initiatives as a serious strategy for sustainable lifestyles, but also launches the challenge of extending input output accounting to capture value beyond market transactions.

Third, future MRIO-based analysis could be more robust when coupled to bottom-up physical data, as we did for PAPERII. Many environmentally relevant lifestyles' aspects lie beyond the traditional scope of input-output modelling. For example, non-technical visions that encourage co-habitation (persons per dwelling) and downsizing of houses (area per person) might have significant potential, but require different assessment tools[107,155]. Bottom-up physical data on technology ownership, infrastructures, material stocks[11] and user practices reported by socio-economic group allows for the study of lock-ins and non-technical options.

Fourth, by focusing mainly on households we overlook the role of political regimes and public investments. These agents provide need satisfiers to households and, by doing so, uptake some of the environmental impact that technically belongs to households[36] (only considered in PAPER I). The same goes for capital formation[156], as arguably a portion of road and parking infrastructure could be attributed to households vehicles, even if they are built by public or private sectors[11]. Built capital and infrastructure drive about 24% of global emissions[29,41] and are currently excluded from our analysis. Future research would quantify capital in place and distinguish private from public capitals in regards to their eco-efficiency to address needs[22]. Further research would simultaneously model the relationships between different type of capitals[29–31], planetary boundaries[15] and represent social heterogeneity[1,11].

Finally, this research is policy informative but not prescriptive. Further efforts could test the effect of specific demand-side policies for environmental mitigation. Capping discretionary consumption, progressive taxation, reducing working time, universal basic income and heavy regulation of environmentally intensive goods that hinder well-being are examples of interesting policies that are suggested in this thesis but that require further scientific research. In this direction, assessments models would integrate theoretical and empirical work from economics and social sciences for a robust modelling of human-economy-nature interactions.

3.4 Thesis overview



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Appendix:

PAPERS

I. **Vita,G**.;Hertwich,E.G.; Stalder,K.; Wood,R. (2018) Connecting global emissions to fundamental human needs and their satisfaction. Environmental Research Letters.

II. **Vita, G**; Lundström, R; Quist, J.; Stadler, K.; Ivanova, D.; Wood, R. and Hertwich, E.G. Sustainable lifestyle scenarios to curb European environmental impact: Connecting local visions to global consequences (2018). Under review with Ecological Economics.

III. **Vita, G***. ;Ivanova, D*.; Dumitru, A.; García-Mira, R.; Carrus, G.; Stadler,K.; Krause ,K.; Wood, R.; Hertwich, E.G. The potential of grassroots initiatives to reduce carbon emissions and enhance well-being. (2018). Under review with Environmental Research Letters *Shared first authorship

IV. **Vita, G**.; Narasimha, R.; Usubiaga, A.; Min,J.; and Wood, R. The energy footprints of household durables, consumables and services: A global study from 1995 to 2011 (2018), in preparation.

V. Vásquez, F*.; **Vita, G***.; Müller, D. Food security for an ageing and heavier population (2018). Sustainability *Shared first authorship.

PAPER I

Connecting global emissions to fundamental human needs and their satisfaction

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APP Template V1.00 Article id: erlaae6e0 Typesetter: MPS Date received by MPS: 11/10/2018 PE: MAC007125 CE: LE: UNCORRECTED PROOF

IOP Publishing *Environ. Res. Lett.* **00** (2018) 000000

Environmental Research Letters

CrossMark

OPEN ACCESS

RECEIVED
6 March 2017

REVISED
6 October 2018

ACCEPTED FOR PUBLICATION
9 October 2018

PUBLISHED
DD MM 2018

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LETTER

Connecting global emissions to fundamental human needs and their satisfaction

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Keywords: fundamental human needs, mixed methods, environmentally extended multi-regional input–output analysis (EXIOBASE), Max-Neef, carbon & energy footprints, environmental sociology, sustainable wellbeing

Supplementary material for this article is available online

Abstract

While quality of life (QOL) is the result of satisfying human needs, our current provision strategies result in global environmental degradation. To ensure sustainable QOL, we need to understand the environmental impact of human needs satisfaction. In this paper we deconstruct QOL, and apply the fundamental human needs framework developed by Max-Neef *et al* to calculate the carbon and energy footprints of *subsistence*, *protection*, *creation*, *freedom*, *leisure*, *identity*, *understanding* and *participation*. We find that half of global carbon emissions are driven by *subsistence* and *protection*. A similar amount are due to *freedom*, *identity*, *creation* and *leisure* together, whereas *understanding* and *participation* jointly account for less than 4% of global emissions. We use 35 objective and subjective indicators to evaluate human needs satisfaction and their associated carbon footprints across nations. We find that the relationship between QOL and environmental impact is more complex than previously identified through aggregated or single indicators. Satisfying needs such as *protection*, *identity* and *leisure* is generally not correlated with their corresponding footprints. In contrast, the likelihood of satisfying needs for *understanding*, *creation*, *participation* and *freedom*, increases steeply when moving from low to moderate emissions, and then stagnates. Most objective indicators show a threshold trend with respect to footprints, but most subjective indicators show no relationship, except for *freedom* and *creation*. Our study signals the importance of considering both subjective and objective satisfaction to assess QOL-impact relationships at the needs level. In this way, resources could be strategically invested where they strongly relate to social outcomes, and spared where non-consumption satisfiers could be more effective. Through this approach, decoupling human needs satisfaction from environmental damage becomes more attainable.

Introduction (1237)

Sustainable development and quality of life (QOL) share a focus on human needs. Sustainable development is defined as satisfying human needs without compromising natural and social capital [1] while QOL is a result of satisfied physical, psychological, and social needs [2–4]. Needs can be satisfied by immaterial means [2, 4], such as good health or social relations [4], or material ones, such as economic goods and infrastructures [4–6]. The goal of sustainability is to achieve high QOL while preserving the natural environment [1, 7, 8]. The status-quo is to pursue high QOL through rampant consumption [7], which invariably leads to environmental damage [9, 10] but does not necessarily satisfies needs [11–13]. A step towards more sustainable strategies for enhanced QOL is to clarify the interaction between needs satisfaction, consumption, and environmental impact [2, 5, 11, 14].

Different theories of environmental sociology propose relationships between economic growth, environmental degradation and QOL. Modernization theories, including ‘economic and ecological modernization’,

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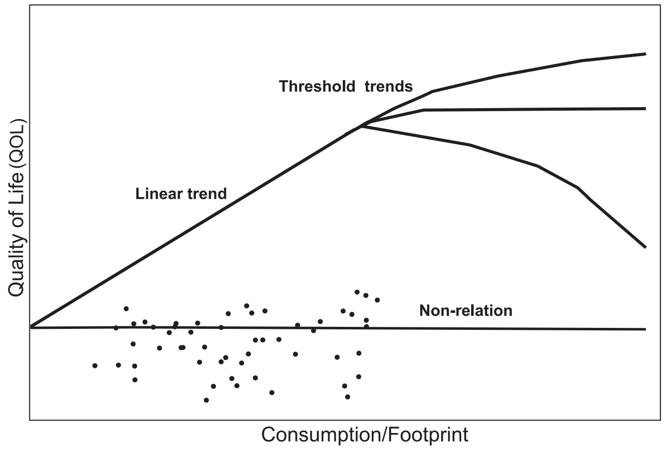

Figure 1. Proposed trends between consumption and quality of life in relation to development theories [2, 4, 5, 7, 11, 12, 19, 21, 22]. N. B.: In this paper, footprints are a direct function of consumption [9, 23] (see Methods).

argue for the positive role of economic growth and consumption in achieving sustainability and improving QOL [12, 15, 16]. These theories rely on assumptions of neoclassical economics and thus predict a strong link between consumption or impact and QOL, represented by the linear positive relationship shown in figure 1.

In contrast, the 'treadmills of production' theory states that, due to its expansive nature, economic growth is in fundamental conflict with environmental protection [12, 16]. This theory predicts that modern nations reach a point of 'decreased social efficiency of natural resource utilization', where initial steep increases in QOL might correlate with increasing carbon footprint but reach a threshold of diminishing returns and eventually a steady state [17] (figure 1). After this threshold, each consumption unit generates more environmental damage and less welfare than it did at lower levels of development [12]. In some cases, QOL can even decline when increased consumption results in more harm than benefit [2, 12].

The theory of 'human ecology' considers a broader context, recognizing that QOL might also be affected by non-consumption factors [16] such as social dyanmics [18], relationships [19], health [3], climate conditions [12, 16], political factors [5, 16], etc (see [12, 16, 20]). In this case, changes in consumption do not necessarily predict changes in well-being, as shown by the 'non-relation' constant or scatter plots in figure 1. The supplementary information (SI1 is available online at stacks.iop.org/ERL/0/000000/mmedia) presents a summary of the trends and related concepts from other disciplines that link consumption and non-consumption to QOL.

Empirical evidence: QOL and environmental impact

Empirical findings of threshold and weak relations between QOL and consumption point to the opportunity of reducing impact without affecting the QOL in wealthy nations [7, 24–26]. Early evidence for the threshold pattern was demonstrated by the Easterlin Paradox [27], where consumption positively correlates with QOL but only up to a point and not over the long term [27, 28]. Further investigations argued for a trend of diminishing returns between QOL and consumption [29–31]. Nevertheless, both trends concede that additional consumption yields steeper benefits to the QOL of the poor, compared to the rich [19, 31]. Although studies confirm the Easterlin Paradox at different geographical scopes [12, 24, 32], they generally overlook using subjective life satisfaction as an adequate proxy for needs satisfaction [31, 33], and of using economic proxies for resource use (SI1 and SI5).

Sustainability-oriented studies further confirm threshold relationships between objective indicators of QOL, energy use [14, 25, 26, 34–36] or carbon footprint [12, 13, 24, 37–41]. The marginal benefit of additional CO_2 emissions, as measured by increased QOL, quickly decreases at a carbon footprint of around 3 tons CO_2 per capita (t CO_2/cap) [13, 37] and becomes indistinguishable from zero at values above 10 t CO_2/cap [13, 34, 37]. A QOL-CO_2 threshold has been reported for several indicators of QOL, including life expectancy [34, 37, 38, 41], infrastructure access [13, 35, 36], education [5, 24, 26] and the Index of Sustainable Economic Welfare [17, 42]. These findings signal opportunities for resource efficient development by directing resources to areas that have demonstrable social benefits [5, 8], such as child-rearing [4, 17], education [24, 43], access to energy [35], nutrition [13, 39] and sanitation [13]. However, most measures of environmental impact have been limited to national footprints [24, 37, 41] or consumption domains [9, 10].

Policymakers and the general public are eager for measures of progress in terms of societal outcomes rather than monetary inputs (e.g. healthy people rather than investments in the health sector) [5]. A multidimensional approach to the QOL-impact relationship considers the underlying human needs that enhance QOL [8] and whose satisfaction ultimately drives impact [14]. Apart from few exceptions [24], most studies measure QOL through single, composite, or broad indicators, such as life expectancy [36–38, 41], human development index [34], or life satisfaction [12, 27–30, 32], respectively. However, QOL not only depends on the level to which human needs are objectively met, but also on peoples' subjective satisfaction with respect to such levels [3, 8]. Initiatives such as the Better Life Index [44] or the Social Progress Index [45] demonstrate the complementarity of objective and subjective indicators for sounder policies [8].

Assessing environmental impact and satisfaction of fundamental human needs

We apply the framework of fundamental human needs to study the link between sustainability and QOL [2]. Max-Neef and colleagues recognized the bias of studying consumption and QOL based on consumption domains (e.g. transport, housing) [9, 23] rather than looking at their contribution to life domains (e.g. work, leisure, health) [3]. They proposed that all that we have and do, as well as the spaces in which we interact and the skills we build, are potential 'satisfiers' that contribute to QOL. In their view, QOL is a consequence of satisfying nine fundamental human needs: *subsistence*, *protection*, *creation*, *identity*, *affection*, *participation*, *understanding*, *leisure* and *freedom* [2]. These human needs are immutable across societies and throughout time. While other frameworks define universal saisfiers [46], Max-Neef argues that strategies to satisfy needs are entirely flexible and determined by each individual or group. Thus, satisfiers can be sustainable or unsustainable, based on different types of capital: natural, social and cultural [47].

We find this framework useful as it encompasses the QOL-consumption relations described in figure 1 [2]. Further, the concept of satisfiers for needs is comprehensive and inclusive of market and non-market goods. In contrast to similar frameworks [48], Max-Neef provides abundant examples that can be used as guidelines to model goods as satisfiers and to choose indicators of need satisfaction (SI table 3) [49]. Unlike the hierarchical taxonomy of Maslow [50], a horizontal view of needs is supported by robust research that proves needs to be fairly independent of each other [19]. For example, individuals with low material living standards can have better psychological and social well-being than their well-off counterparts [18, 19, 32, 51].

We take a multi-dimensional approach to QOL [3, 8] by applying the framework of fundamental human needs. As others before us, we model economic goods as satisfiers [47, 52] as a basis to estimate the energy and carbon footprints of fundamental human needs at a global and country level [53]. We then perform a cross-sectional analysis of 35 different objective and subjective indicators of needs satisfaction as a function of their footprints across 44 nations. To our knowledge, this is the first study to provide global and country-level estimates of the carbon and energy associated with fundamental human needs and their satisfaction.

Methods (1206)

This study linked final consumption of market goods and services to the needs that they allegedly satisfy. This made it possible to calculate consumption and associated energy and carbon footprints for each human need at the country level. We then assessed needs satisfaction across nations and examined the relationship when plotted against each need's carbon footprint. All footprints calculations and most QOL indicators are for the year 2007, unless otherwise specified in the SI (appendix).

Linking economic goods to human needs

First, we proposed a correspondence between the 200 economic goods available in the input–output database (EXIOBASE3-2007 [54, 55]) and the nine human needs [2] as show in step 1 of table 1. Through group discussions, we discarded the most unlikely relationships between market goods and needs following Max-Neef's taxonomy and examples as guidelines [2, 49]. In the development of the correspondence matrix, we established conceptual identities between goods and needs to use as a guiding logic [2, 49] (see SI2 for details). As a result, *subsistence* relied heavily on food and housing, and to a lesser extent on transport and manufactured goods. *Protection* included health care, safety and financial security and can be satisfied by a range of goods, from insurances to heating fuels. *Creation* included the means to create and exercise creativity in both formal and informal work, as well as the application of art and crafts skills to material objects [56]. *Freedom*, understood as spatial and temporal plasticity, relied on market items that save time such as transport, domestic appliances and services (e.g. outsourcing of household work). *Leisure* included transport and energy for pleasure, as well as recreational services and entertainment. *Identity* relates mostly to goods that enable expression of preferences such as luxury items, clothing or diets. *Participation* related to communication media devices and club memberships, while *understanding* associated to diverse pedagogic goods, from computers to educational services. *Affection* was not linked to any market good in the database and is therefore not included in this analysis.

A novelty of our model is to allow one market good to satisfy several needs simultaneously as 'synergistic satisfiers'[49]. For example, purchasing food directly satisfies *subsistence* but also *identity,* as reflected in diet and cuisine. We recognized that *subsistence* and *protection* are more directly reliant on material prerequisites compared to other needs (*participation*, *identity*, etc) [7, 24, 40]. Accordingly, we derived an allocation key based on the expenditure ratios between the lowest and highest income groups for each type of market good [40] by assuming that discretionary expenditure in synergistic basic goods aims to satisfy non-physical needs [40]. For example, if people in the lowest income quintiles spent on average 30 USD per capita

Table 1. Steps 1 and 2 establish a correspondence matrix between economic goods and fundamental needs. Step 3 characterizes the uncertainty in step 2. This procedure was conducted for 200 economic goods. Su: Subsistence, Pr: Protection, Af: Affection, Un: Understanding, Pa: Participation, Le: Leisure, Cr: Creation, Id: Identity, Fr: Freedom. Full concordance matrix available in the supplementary data.

Step 1. Concordance	Su.	Pr.	Af.	Un.	Pa.	Le.	Cr.	Id.	Fr.	
Clothing	1	0	0	0	0	0	0	1	0	Focus group to establish a match between products and needs by discarding relationships (0s) according to Max-Neef's examples
Waste management	1	1	0	0	0	0	0	0	0	
Step 2. Allocation										
Clothing	0.2	0	0	0	0	0	0	0.8	0	Allocation ratios for synergistic goods according to the expenditure ratio between higher/lower quintiles for each good type (US survey)
Waste management	0.5	0.5	0	0	0	0	0	0	0	
Step 3. Uncertainty test										
Clothing	X	0	0	0	0	0	0	X	0	Characterize the uncertainty of using US data by running a Monte Carlo simulation to test all possible splits in X
Waste management	X	X	0	0	0	0	0	0	0	

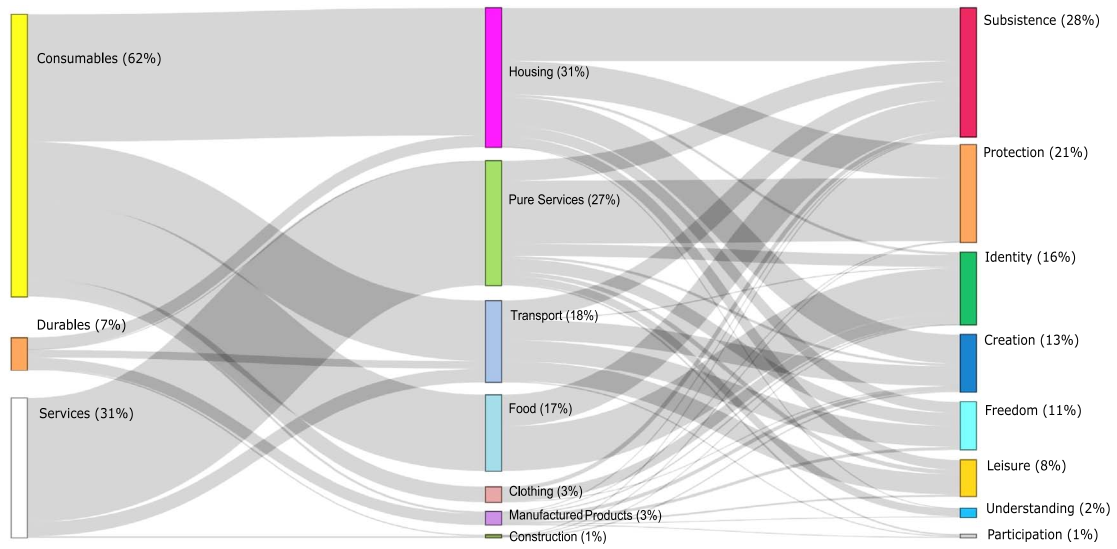

Figure 2. The global carbon footprint embodied in human needs under different classifications of goods. Results represent global final consumption by households, governments and non-profit serving households in 2007. The global carbon emissions embodied in consumption for 2007 amounts to 28 Gt CO_2 eq. The figure displays the links between three different aggregations of the 200 market goods in EXIOBASE3 by type of consumer good, classified as durable goods, non-durable goods and services (left), by consumption category or functionality (middle) [23] and by human needs they satisfy [49] (right). The equivalent figure for global energy footprint is available in the SI (figure 2). NB: The Sankey diagrams only reflect embodied emissions, additional 5 Gt CO_2 eq make up direct household emissions which are considered for the results under 'carbon emissions and need satisfaction'.

on clothing, while the highest income quintiles spent 100 USD/cap, we allocated 30% of the total expenditure on clothing as a satisfier for *subsistence* whilst the remaining 70% went to *identity*. We used a US expenditure survey [57] to derive ratios and split synergistic satisfiers between basic needs (*subsistence* and *protection*) and other needs (step 2 table 1).

Finally, we conducted a Monte Carlo simulation to characterize the uncertainty of generalizing the allocation ratios from step 2 to the global economy. By testing all possible splits, we find the same relative hierarchy of the needs' carbon footprints and our values fall within the interquartile range of dispersion (see SI2). While the allocation values can certainly be refined by using country-specific data, our initial estimate proved to be robust and generalizable.

Footprints and consumption of needs

Consumption footprints consider all the energy and carbon emissions embodied in the production of goods, and attribute them to final consumers. In this sense, the carbon footprint of a nation equals the direct emissions occurring due to households' transport, heating and cooking, plus the embodied impact in the production of all consumed goods and services [53]. We model the final demand of households, governments, and non-profit institutions serving households for the year 2007, assuming that they all consume to satisfy societal needs.

We used the standard Leontief Input–Output model [58] to calculate energy and carbon footprints for 2007 based in EXIOBASE3, an open-access environmentally extended multiregional input–output database [55, 59] that captures the global economic activity and resources. We consider both combustion and non-combustion greenhouse gases (CO_2, CH_4, N_2O and SF_6) [55] normalized to carbon dioxide equivalents (CO_2eq) by using the IPCC 2007 characterization factors [55]. The net energy footprint includes the primary and secondary energy carriers used by industries for production of goods [55, 60]. Details about the footprints calculations are found in the SI3 [55, 60]. EXIOBASE3 covers the 44 largest economies, which make up 91% of global GDP and 65% of the world population. The rest of the world is represented by five regions of Middle East, America, Europe, Asia Pacific and Africa [55]. The global carbon and net energy footprints embodied in consumption are used for the first section of results i.e. including the Rest of the World regions (figures 2 and 3). Embodied plus direct household energy and emissions were considered to compute footprints of needs across the 44 individual countries and assess need satisfaction (figure 4 and table 4). Finally, by applying the concept of consumption and footprint elasticity [9, 23], we compared marginal differences in consumption and footprints with respect to differences in the total consumption associated to needs (see SI3).

Assessing need satisfaction and QOL-footprint trends

Table 2 presents our dashboard of indicators, compiled under the following heuristics [8]: (1) QOL is multidimensional and should be measured in terms of specific human needs; (2) the evaluation of multiple needs should combine different scales: from individuals to societal level; (3) combining subjective and objective measures is

Figure 3. Average embodied energy (a) and carbon (b) intensities, carbon footprint (c) of needs for different groups of nations in 2007. Higher income (gray line) groups the 21 wealthiest nations (866 million people). Lower income (yellow line) groups the 22 less wealthy nations (3.4 billion people), of which 2.8 billion live in Brazil, Russia, India, China and South Africa (BRICS, blue line). World Average includes Rest of the World regions (Africa, Europe, America, Asia and Pacific). Groups of nations, footprint values and economic data are available in the SD.

necessary to understand the important inputs for improving QOL. We combine objective and subjective indicators of satisfaction for each need at a national level. To guide our selection of indicators, we referred to Max-Neef's examples of satisfiers for the existential categories of 'being' and 'doing' [2, 49] (see SI3 and SI table 1). Detailed considerations and rationale for indicator choice are found in the SI.

Subjective well-being indicators are self-reports that capture the percentage of individuals who are satisfied with respect to a need. When available, we included measures of values to represent the importance of a certain need for a population [61]. Objective indicators are assessed by a third party and used to represent infrastructure, social institutions, or health status [5, 8]. For example, to assess the subjective satisfaction of *freedom* we used the question: 'are you satisfied with freedom to choose what do with your life?' [62]. To assess the importance of freedom, we used the Schwarz scale item: 'it is important to take own decisions. She/he likes to be free and not depend on others' [63]. To measure the objective status of freedom in a country, we took the measure of tolerance, inclusion, and personal rights reported in the Social Progress Index [45]. We compiled 35 indicators from the databases (see table 2). When sensible, we prioritized single over composite indicators to prevent conceptual overlaps. However, objective indicators for freedom, democracy, and creativity do cover several dimensions. See the SI for the full referenced inventory of indicators for each need and the measure of satisfaction rates (appendix).

Using 'need satisfaction rate' as the dependent variable and the 'per capita carbon footprint of need' as the independent variable, we ran unweighted cross-country bivariate regressions to test the association between carbon footprint of needs and satisfaction outcomes (see SI 5). The mathematical forms of the models are, respectively:

$$Y_{ji} = \beta_o + \beta_1 CF_{ni} + \upsilon_{ni} \tag{1}$$

$$Y_{ji} = \beta_o + \beta_1 CF_{ni} + \beta_2 CF_{ni}^2 + \upsilon_{ni} \tag{2}$$

$$Y_{ji} = \beta_o CF_{ni}^{\beta_1} + \upsilon_{ni}, \tag{3}$$

where Y is the reported satisfaction rate for each indicator j of each need i. CF is the per capita carbon footprint of each need i, in every nation n. The β

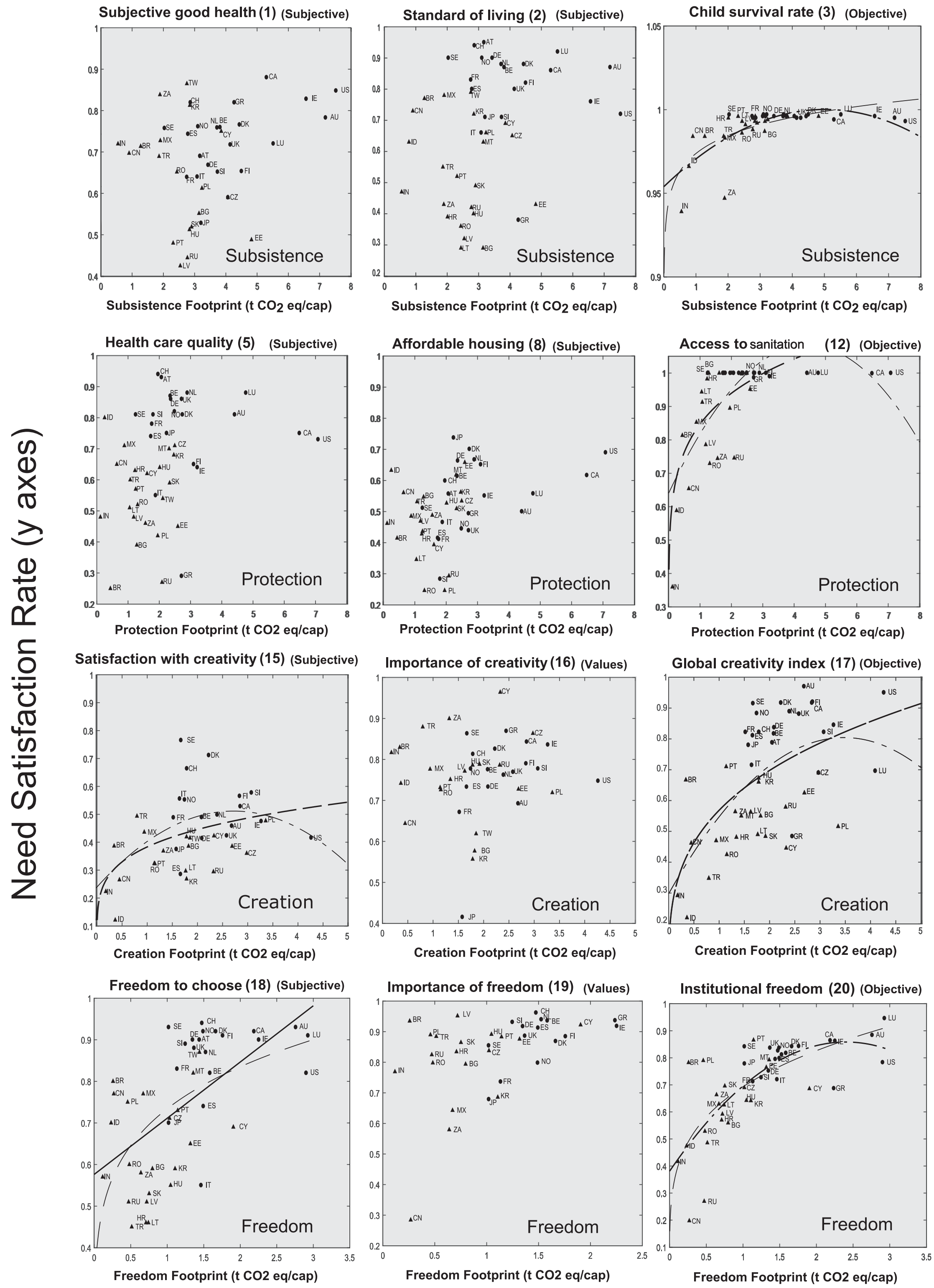

Figure 4. (a) Plots of need satisfaction (*y* axes) against carbon footprint of needs (*x* axes) for each country in 2007. The two best fitting models ($R^2 > 0.28$) appear on the plot represented by linear (—), quadratic (- — -) and power law (— —) and the best fit is bolded. Key: 'Freedom to choose' fits a linear trend while 'Importance of freedom' is scattered and 'Institutional Freedom' fits a curvilinear trend. ● = higher income nations ▲ = lower income nations. N.B. The additional plots for Subsistence, Protection, Understanding and 'general' well-being are available in the SI. (b) Plots of need satisfaction (*y* axes) against carbon footprint of needs (*x* axes) for each country in 2007. The two best fitting models ($R^2 > 0.28$) appear on the plot represented by linear (—), quadratic (- — -) and power law (— —) and the best fit is bolded. ● = higher income nations ▲ = lower income nations. N.B. The additional plots for Subsistence, Protection, Understanding and 'general' well-being are available in the SI.

coefficients are constants that result from the fit and υ is the error term. The cut-off criteria to accept a model fit between carbon footprint and need satisfaction is an adjusted R^2 above 0.28, while the criteria to accept a statistical significant relationship is set at 5% (p-value $<$0.05) for all the relationships investigated: linear,

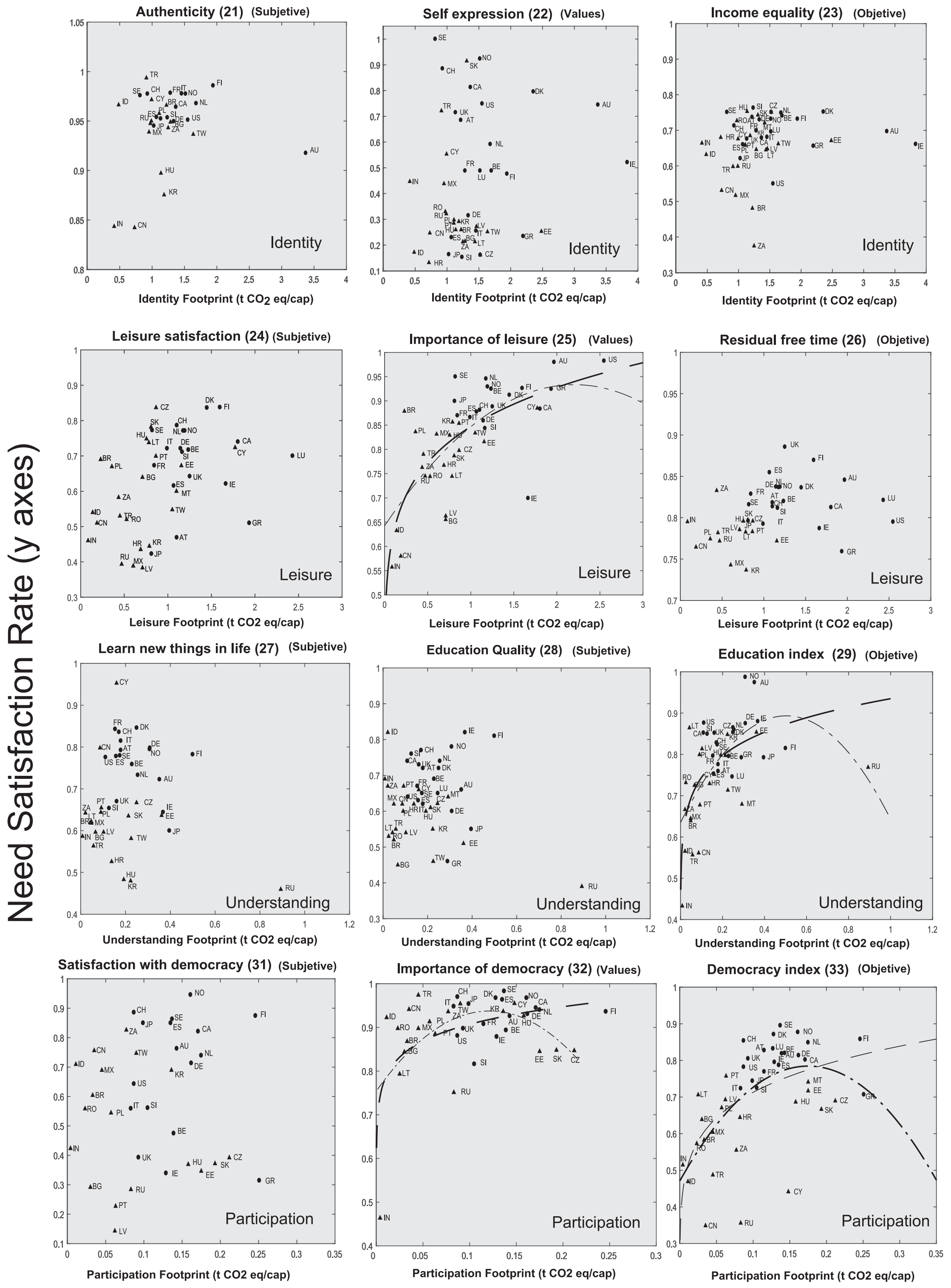

Figure 4. (Continued.)

quadratic and power law. In similar studies, objective indicators often yield an R^2 above 0.5, while for subjective or social indicators, values lower than 0.25 are commonly accepted, given statistical significance [13, 24, 75]. Because we combine an assortment of indicator types and given our sample size ($40 < N < 50$), we establish our criteria seeking to discard weak evidence.

We hypothesize that linear curve fits support the theory of 'ecological modernization' while nonlinear fits sustain the 'treadmills of production' theory. A significant power-law fit would imply diminishing returns on QOL. Quadratic fits might indicate saturating thresholds or even declining QOL, given a negative significant coefficient. Non-relationships might be explained by factors of human ecology [12]. However, we do not account explicitly for such factors and thus cannot confirm not discard their role.

Table 2. Indicators by type and data sources. Thirty-five indicators were compiled to use as proxy for human need satisfaction. When different data sources had identical questions, we combined them to prevent missing data points. All indicators report 2007 data unless otherwise specified in the SI appendix.

Type of indicator	Data sources
Objective indicators	
Child survival rate, democracy index, non-obese adults, long term employment, inverse homicide rate, inverse fertility rate, access to sanitation, access to modern fuels, access to electricity, global creativity index, institutional freedom, income equality, residual free time, increased knowledge, education index, reading comprehension	Social progress index [45]
	World bank indicators [64]
	Central intelligence agency [65]
	World health organization [66]
	Global democracy ranking [67]
	The global creativity index [68]
	OECD labour force and time use [69, 70]
	Programme for International Student Assessment (PISA) [71]
Subjective indicators (satisfaction and values)	
Subjective health, standard of living, health care quality, feeling safe, satisfaction with labor market, affordable housing, satisfaction with creativity, freedom to choose, authenticity, leisure satisfaction, importance of leisure, importance of freedom, importance of creativity, self-expression, learn new things in life, satisfaction with democracy, importance of democracy, overall life satisfaction	Human Development Report :UNDP [62]
	World Value Survey [72]
	European Social Survey [73]
	International Social Survey [74]

Results (1800)

Carbon footprints of human needs

At a global level, *subsistence* drives 28% of global emissions followed by *protection, freedom, identity,* and *creation* (figure 2). While food is important, housing contributes the largest share of the carbon footprint of *subsistence*. *Protection* has the second highest carbon footprint with 21% of global emissions and the highest expenditure, in line with previous findings which trace 50% of impact to *subsistence* and *protection* [52]. *Freedom* and *identity* together make up around 27% of global emissions. *Creation* and *leisure* underlie around 21% of the total carbon emissions, while *understanding* and *participation* amount about 3% of the total carbon footprint. Figure 2 presents the linkages between human needs and the common categorization of goods by consumption domains (housing, services, mobility, etc). The supplementary data contains the expenditure and footprints of human needs for the 44 nations and 5 world regions.

Marginal changes and environmental intensity of needs

Creation is the most intensive need with a world average of 2.6 kg CO_2 eq and 17 MJ per EUR of expenditure, followed by *subsistence* and *leisure* (figures 3(a), (b)). By contrast, *understanding* and *protection* are the least intensive, due to the large share of services that they require [9] (figure 2). The 22 poorest nations of our sample expend 2–4 times more carbon and energy per unit of consumption, compared to the 22 wealthiest (figures 3(a), (b)). However, the low intensity of wealthy nations is counteracted by consumption volume, resulting in 2–7 times higher footprints, compared to the poorest nations, e.g. twice the carbon footprint for *understanding* and *participation*, 4 times higher for *subsistence* and up 7 times higher for *protection* and *leisure* (figure 3(c)). These trends point to the role of economic development in lowering the carbon intensity of human needs [9, 10]. However, it also signals that the benefits of more efficient technical systems and lower intensities are undermined by exacerbated consumption via the rebound effect [76, 77].

Brazil, Russia, India, China and South Africa (BRICS) have the lowest footprints per capita, but the highest impact intensities. Since 2.8 billon people inhabit the emergent economies of the BRICS group, the current footprint differences between wealthy nations and the BRICS (figure 3(c)) signals the potential for increased emissions in the coming decades. It is worth noting that all groups of nations show a similar distribution of carbon among needs, and only the magnitudes vary (figure 3(c)). This is not the case when looking at consumption categories (figure 2), where poor nations tend to concentrate emissions in food and housing [9, 23].

We used elasticities to test the sensitivity of changes in consumption and footprints of needs with respect to changes in total expenditure (table 3). A 1% increases in total consumption corresponds to more than 1% increases in the consumption of most needs ($\varepsilon > 1$), except for *subsistence*, *identity* and *freedom,* which change at decreasing rates ($\varepsilon < 1$). Carbon and energy footprints both change at decreasing rates with

Table 3. Elasticities (ε) of needs indicate the percent change in the indicator (footprints or consumption) for each need with respect to a 1% increase in total consumption. All reported coefficients are significant to an alpha of 1%. ε is the $\beta 1$ slope resulting from regressing the log–log transformed version of equation (1). The dependent variables are per capita consumption and footprints for each need and the independent variable is total expenditure for the sample of 44 nations.

	Consumption		Carbon footprint		Energy footprint	
	ε	R^2	ε	R^2	ε	R^2
Subsistence	0.99	0.99	0.49	0.75	0.43	0.77
Protection	1.09	0.97	0.60	0.70	0.47	0.76
Freedom	0.98	0.97	0.65	0.85	0.45	0.81
Identity	0.87	0.96	0.35	0.55	0.29	0.41
Creation	1.01	0.97	0.57	0.69	0.45	0.72
Leisure	1.01	0.98	0.68	0.84	0.46	0.79
Participation	1.10	0.93	0.68	0.69	0.57	0.62
Understanding	1.09	0.91	0.67	0.55	0.51	0.46

respect to expenditure. However, the carbon footprint of needs is slightly more sensitive to consumption changes [9]. *Protection*, *leisure*, *participation* and *understanding* are some of the most sensitive needs, as shown by a higher ε coefficient. On the contrary, *identity* is one of the least sensitive, as it is satisfied by a large share of food products (figure 2), which are basic goods [10].

Carbon emissions and need satisfaction

When assessing needs satisfaction, we observe no universal pattern between the degree of satisfaction and the carbon emissions expended in those needs (figures 4(a), (b)). The threshold pattern found in previous studies [13, 24, 27, 28, 34, 36, 37] is confirmed for 14 indicators; 11 of which are objective, 2 value indicators and 2 subjective. We only find evidence for a linear trend when assessing subjective *freedom*, discussed below. For 20 out of 35 relationships investigated, we find no correlation between the carbon footprint of human needs and their satisfaction. The diversity of relationships becomes evident when exploring figures 4(a), (b). Table 4 summarizes the model fits for all 35 tested relationships. The adjusted R^2 indicates how well the carbon footprint predicts needs satisfaction i.e. the strength of the relationship (see the SI for full statistics). Regression coefficients greater than 1 imply that likelihood of satisfaction varies more than proportionally with footprints; values between 0 and 1 indicate that satisfaction changes at diminishing rates with respect to footprints. Negative coefficients indicate a negative correlation between satisfaction and footprints.

Subsistence

Subsistence is the need with the largest carbon footprint (figures 2 and 3(c)). The childhood survival and inverse fertility rates increase steeply at low emissions and stagnate around 2 t CO_2eq/cap, which is about 1 ton above the threshold reported for life expectancy [37]. The subjective satisfaction with health and living standards is not correlated to consumption of *subsistence* goods and footprint.

Protection

Due to its multi-dimensional nature, we measure *protection* with ten indicators. While *protection* has the second largest footprint, seven out of ten indicators are not related to the footprint of *protection*. Health care quality, feeling safe, satisfaction with labor market, affordable housing, non-obese adults, long-term employment and the probability of not being murdered (inverse homicide rate) are all measures of *protection* that seem unrelated to carbon emissions as show in table 4 (Indicators 5–11). Nonetheless, the infrastructure dimensions of *protection*, such as access to modern fuels, electricity and sanitation seem to improve rapidly with moderate increases in resources destined to *protection*, in line with previous findings [13, 35, 36]. In line with recent studies, we find that access to sanitation and energy infrastructures are nearly fully satisfied at a *protection* footprint of 3 t CO_2eq/cap [13, 24]. The curvilinear shape of these plots is driven by few emerging infrastructures [13, 35]. European countries such as Spain, Italy, Portugal and France with a *protection* footprint below 2 t CO_2eq/cap manage to provide virtually 100% of access to modern fuels and sanitation. See the SI for the remaining plots of the *protection* indicators not shown in figure 4.

Identity

None of the indicators of *identity* satisfaction trend with emissions. The satisfaction with respect to individual authenticity proves to be universal and independent of consumption, with a satisfaction level above 90% across nations. Most nations in our sample report an income equality of 60%–80% and thus equality does not vary with footprint [24]. Self-expression values represent environmental awareness, tolerance and social engagement. Countries with low self-expression are more loaded with survival values, which prioritize security, conformity and low levels of trust and tolerance [61]. We find that self-expression differs widely for countries with similar *identity* footprint (e.g. see Mexico and Sweden). Ingelhart and Welzel recognize that collective values may be heavily influenced by factors of human ecology such as cultural practices and political history, rather than wealth [61].

Creation

Subjective satisfaction with creativity at the workplace and objective measures of creativity (global creativity index) are steeply correlated with *creation* footprints up to a threshold of around 2 t CO_2/cap. *Creation* satisfaction is coupled to opportunities for skilled and gainful work in high income nations [3, 56], rather

Table 4. Tested relationships between needs satisfaction and carbon footprint of needs. Strong relationships are highlighted in gray. The 'trend shape' column describes the visual trend of the data plot (figure 1). The 'best fit' was selected among power law (pl), quadratic (qu) and linear (lin) fits when the adjusted coefficient of determination (R^2) is above 0.28. The second best fit is provided in 'Alt-fit' column and the relationship is validated with energy footprint. The slopes report unstandardized coefficients and the symbols *, ** and *** denote significance levels, α, of 10%, 5% and 1%, respectively.

				Carbon footprint						Energy footprint (Validation)		
Human need	Type	Indicators	Trend shape	Best fit	*B* coeff	Adj. R^2	Alt-fit	*B* coeff	Adj. R^2	Best fit	*B* coeff	Adj. R^2
Subsistence	Subjective	Good health (1)	Non-relation	Quadratic	−5.50	0.09				qu	−0.5	0.10
	Subjective	Standard of living (2)	Non-relation	Linear	4.1^{**}	0.07				lin	0.6^{***}	0.19
	Objective	Inverse Fertility Rate (3)	Threshold	Quadratic	1.8^{***}	0.51	pl	1.6^{***}	0.47	qu	0.2^{***}	0.53
	Objective	Child survival rate (4)	Threshold	Quadratic	13.5^{***}	0.40	pl	12.2^{***}	0.20	qu	1.3^{***}	0.44
Protection	Subjective	Health care quality (5)	Non-relation	Quadratic	10.3^{*}	0.09				qu	1.1^{***}	0.18
	Subjective	Feeling safe (6)	Non-relation	Linear	2.6^{*}	0.05				lin	0.3^{**}	0.11
	Subjective	Satisfaction with local labour market (7)										
	Non-relation	power	−12.50	0.00				pl	−16.2	0.01		
	Subjective	Affordable housing (8)	Non-relation	Linear	3.4^{**}	0.13				lin	0.3^{***}	0.16
	Objective	Non-obese adults (9)	Non-relation	Power	-5.4^{***}	0.18				pl	-4.4^{**}	0.11
	Objective	Long-term employment (10)	Non-relation	Linear	0.60	0.03				lin	0.1^{**}	0.07
	Objective	Inverse homicide rate (11)	Non-relation	Quadratic	4.6^{**}	0.06				qu	0.3^{**}	0.06
	Objective	Access to sanitation (12)	Threshold	Power	20.3^{***}	0.62	qu	20^{***}	0.50	pl	20.7^{***}	0.60
	Objective	Access to modern fuels (13)	Threshold	Power	17.7^{***}	0.54	qu	16.3^{***}	0.42	pl	17.7^{***}	0.51
	Objective	Access to electricity (14)	Threshold	Power	3.9^{***}	0.29	qu	4.1^{***}	0.14	pl	3.7^{***}	0.25
Creation	Subjective	Satisfaction with creativity (15)	Threshold	Power	27.8^{***}	0.29	qu	19.4^{**}	0.19	qu	32.8^{***}	0.34
	Values	Importance of creativity (16)	Non-relation	Linear	1.10	−0.02				lin	0.1	−0.01
	Objective	Global creativity index (17)	Threshold	Power	33.2^{***}	0.40	qu	29.2^{***}	0.33	pl	40.6^{***}	0.51
Freedom	Subjective	Freedom to choose (18)	Linear/Threshold	Linear	13.5^{***}	0.33	qu	22.4^{**}	0.33	lin	1.4^{***}	0.41
	Values	Importance of freedom (19)	Non-relation	Linear	11.2^{***}	0.18				pl	14.4^{**}	0.16
	Objective	Institutional freedom (20)	Threshold	Quadratic	39.8^{***}	0.54	pl	29.8^{***}	0.47	qu	3.4^{***}	0.56
Identity	Subjective	Authenticity (21)	Non-relation	Quadratic	10.9^{**}	0.14				pl	2.9^{**}	0.15
	Values	Self-expression (22)	Non-relation	Power	26.70	0.01				pl	28.9^{*}	0.05
	Objective	Income equality (23)	Non-relation	Power	6.00	0.01				lin	0.5^{***}	0.14
Leisure	Subjective	Leisure satisfaction (24)	Non-relation	Quadratic	27.7^{**}	0.17				lin	1.3^{***}	0.28
	Values	Importance of leisure (25)	Threshold	Power	13.8^{***}	0.53	qu	26.4^{***}	0.46	pl	16^{***}	0.59
	Objective	Residual free time (26)	Non-relation	Quadratic	8.1^{**}	0.16				lin	0.3^{***}	0.24
Understanding	Subjective	Learn new things in life (27)	Non-relation	Quadratic	61.6^{**}	0.12				qu	4.1^{*}	0.02
	Subjective	Education Quality (28)	Non-relation	Quadratic	36.90	0.08				lin	0.3	−0.02
	Objective	Education Index (29)	Threshold	Power	11.4^{***}	0.45	qu	102.6^{***}	0.38	pl	11.8^{***}	0.55
	Objective	Reading comprehension (30)	Threshold	Quadratic	63.4^{***}	0.28	pl	5.2^{***}	0.23	pl	5.5^{***}	0.28
Participation	Subjective	Satisfaction with democracy (31)	Non-relation	Power	4.70	−0.02				qu	−6.4	0.05

Table 4. (Continued.)

Human need	Type	Indicators	Trend shape	Carbon footprint								Energy footprint (Validation)
				Best fit	*B* coeff	Adj. R^2	Alt-fit	*B* coeff	Adj. R^2	Best fit	*B* coeff	Adj. R^2
	Values	Importance of democracy (32)	Threshold	Power	8.4***	0.32	qu	226.8***	0.19	pl	8.1***	0.35
	Objective	Democracy index (33)	Threshold	Quadratic	357.6***	0.34	pl	14.7***	0.27	qu	17.9***	0.45
General	Subjective	Overall life satisfaction (34)	Non-relation	Power	13.4***	0.21				lin	0.1***	0.38
	Objective	Human Development Index (35)	Threshold	Power	14.5***	0.70	qu	3.2***	0.69	qu	0.3***	0.78

than to the consumption of goods associated to *creation*, many of which are defensive goods, which aim to protect current QOL but not necessarily enhance it e.g. driving to work [5], household work (SI table 2). The importance of creativity does not trend with emissions and remains above 70% for most nations (figure 4(a)).

Freedom

Freedom is associated with 11% of the global carbon footprint (figure 2). The subjective satisfaction of *freedom* is the only indicator that shows a linear correlation to *freedom* footprint, however the threshold model offers a comparable good fit (table 4). The finding that 'freedom to choose in life' correlates with its footprint is in line with the capabilities approach by Sen (SI1), who argues that some economic goods that free time, simplify household work or promote synergic need satisfaction, might enable freedom of choice [6, 35]. The importance of *freedom* is fairly high (above 70%) across nations and does not vary with its carbon footprint (figure 4(a)). Institutional freedom stagnates at a value of around 80% of satisfaction corresponding to 1.3 t CO_2eq/cap, pointing to the importance of social institutions in ensuring objective *freedom*, rather than the individual consumption of *freedom*-related goods [5].

Leisure

The importance of *leisure* increases with consumption, suggesting that wealthier societies either tend to perceive less leisure time or value it more [3, 22], despite having similar or slightly more objective free time (see 'expectation-satisfaction gap' in SI). However, this measure does not consider discretionary time by discounting commuting or household work. However, valuing leisure is a trait that emerges in modern societies as they shift towards individualistic values [61]. Noteworthy is that some countries are more eco-efficient than others when satisfying *leisure*: 86% of both Czechs and Danes feel satisfied with their free time at a *leisure* footprint of 1.4 t CO_2eq/cap and 0.86 t CO_2eq/cap, respectively. Objective leisure is rather constant across countries, presumable a consequence of a globalized economy and the influence of organizations such as OECD or International Labor Organization [44, 78] to homogenize labor conditions.

Understanding

We find an association between the carbon footprint of *understanding* and objective satisfaction indicators [24]. The education index displays a strong threshold trend. Nations like Latvia are able to achieve education levels above 80% already at a value of 0.4 t CO_2eq/cap, while nations like Turkey and China attain only 55% of education at 6 and 0.9 t CO_2eq/cap, respectively (figure 4(b)). We find a weaker yet significant relationship to the improvements in reading skills (PISA) with increases in the carbon footprint of *understanding*. Our results confirm a threshold correlation between consumption and objective *understanding* and its satisfaction [24], meaning steeper satisfaction for less wealthy nations. However, subjective satisfaction with learning new things in life and quality of education is not related to increased *understanding* emissions.

Participation

All our indicators for *participation* are limited to the concept of democracy. Objective satisfaction with democracy increases until 0.1 t CO_2eq/cap and stagnates, reaching a maximum value of 75%–85% for the democracy index (figure 4(b)) [24]. The importance of democracy seems to display a threshold trend, but this is clearly driven by an outlier (India) when examined visually. In the remaining nations at least 80% of citizens value living under democratic rule. Similar to education, subjective satisfaction with democracy does not trend with emissions. Notably, given the small carbon footprints of *understanding* and *participation*, results for these needs must be interpreted with caution. The satisfaction of these needs is also enabled by broader structural and social factors [3, 61] (see SI 5 for further considerations).

Overall life satisfaction is the only broad subjective indicator that we used to measure QOL. We do not confirm a strong relationship between life satisfaction and total carbon footprint [24, 28–30] but we do find it for energy [25, 79]. This perhaps points to the fact that energy is more reflective of resource inputs, while carbon represents rather an output, linked to the chosen energy carriers. The Human Development Index does confirm the significant and strong threshold correlation previously reported [34].

Discussion

Overall, we find stronger support for the 'treadmills of production' theory when testing objective measures of QOL, but insufficient evidence for subjective satisfaction. *Subsistence* and *protection* have the largest footprints (figures 2 and 3), yet the satisfaction of health, financial security and personal safety do not correlate to footprints [5] (table 4, Indicators 1–2, 5–11). The 'treadmills of production' theory argues that consumption levels in the past largely determine consumption in the future, regardless of societal outcomes [12, 16, 80]. Similarly, the concepts of defensive expenditures and false satisfiers are characterized by systematic ecological damage through consumption that fails to satisfy needs (SI1) [7, 11, 16, 80]. This seems to be the case for *subsistence* and *protection*, where rising carbon footprint of health care, insurances or public administration does not correlate with citizens being nor feeling healthier [5] nor safer (see 'urban safety' in SI5).

We find greater gains in objective QOL when moving from low to moderate emissions, but diminishing or nil gains at high emissions [7, 17] (see SI5 for further discussion). Moderate increases up to 2 t CO_2/cap in the footprints of *subsistence* and *protection* correspond to steep improvements in the lowering fertility rates, child survival, access to energy and sanitation [13, 35, 36]. The challenge for governments is to satisfy housing, health, financial and personal security regardless of individual consumption and beyond market offer [5]. Policies that promote work-life balance, healthy lifestyles, universal housing and health, or unconditional basic income are interesting options to lower the carbon burden of *subsistence* and *protection* while enhancing needs satisfaction [18, 22, 39, 43].

We find that rising subjective satisfaction of needs is most likely coupled to what people 'are' and 'do' in wealthier economies, rather than to what they happen to consume or own [2, 11]. Except for *creation* and *freedom*, most indicators of subjective satisfaction do not trend with carbon footprints as expected from modernization theories. We rather find correlations among the following indicators of need satisfaction: subjective learning, freedom to choose, creativity and self-expression (SI 4). Satisfaction with creativity at work (*creation*) can enhance the feeling of mastery by using one's full potential on a daily basis [3, 11, 19]. Having vocational skills may play a role in empowering *freedom* of choice for individuals, rather than bearing with circumstances [6, 19]. Interestingly, all subjective satisfaction indicators correlate strongly with overall life satisfaction [19, 31, 44], supporting the importance of individual needs for overall well-being [19, 44, 61].

Policies should tackle subjective satisfaction directly and not solely rely on consumption or objective improvements. Employment structures where people are empowered and develop new skills [19, 56], opportunities for continuous learning [6, 19], and freedom to choose how to spend one's time [7, 22] are all examples of direct satisfiers [7]. Policies could encourage practices that promote intrinsic motivation (instead of materialistic) [81], healthier social norms or 'nudges' to create work and consumption cultures that favor low-impact satisfaction [7, 22, 82]. Bottom-up policies would encourage grassroots initiatives not only to provide sustainable goods–but also to create contexts for social learning [75, 77, 83], cooperation networks and alternative narratives of need satisfaction, such as the voluntary simplicity movement [7, 81, 84].

Human ecology factors can potentially influence those indicators that display high satisfaction levels but do not trend with footprint. For example, cultural idiosyncrasies or psychological resilience might mediate satisfaction with authenticity or learning new things [19, 61]. Institutional factors might influence residual free time, creativity at work, long-term employment and non-obesity rates [3, 5, 78]. Additionally, the importance of *creation, freedom, identity* and *participation* is high and constant across nations (figure 4), which aligns with the notion that needs are intrinsic and universal [2, 19, 50]. However, we cannot support nor reject assumptions from the theory of 'human ecology', as we do not explicitly account for such factors [12, 16].

Future work and limitations

Current theoretical frameworks could expand to consider nuances of QOL-impact relationships. For example, support for 'ecological modernization' might be found through territorial footprints but no longer through consumption-accounting of global impact [12, 38, 41, 85, 86]. Similarly, testing development theories through objective or subjective indicators does influence the results, as we confirm here [12, 38]. Theories could further distinguish the roles of resource flows and stocks for environmental and social stewardship [87]. Resource stocks in the form of hospitals or schools might satisfy QOL as predicted by modernization theories [14]. In contrast, military or vehicle infrastructures might lock-in future resources by perpetuating current practices regardless of social outcomes, as predicted by the 'treadmills of production' [80, 87]. Capital formation and infrastructures drive about 24% of yearly global emissions and are currently excluded from our analysis [9, 88]. Theorizing on the role of equity and access to public and private capitals might enrich our understanding of QOL-impact relationships (see 'unit of analysis' in SI6 [35]).

Our study is a cross-sectional analysis based on middle to high income nations for the year 2007, and thus cannot be directly generalized to low-income nations nor extrapolated into the long-term future. We especially expect infrastructure-related indicators, such as access to sanitation and energy, to flatten out as lagging nations reach decent living standards [13]. However, subjective indicators and those related to social institutions are more coupled to cultural values, social dynamics and human behaviors, and are thus harder to predict [24]. The evolution of their trends will largely depend on the effectiveness of country-specific social systems to satisfy needs. Because subjective satisfaction is generally lower, and mental and emotional-related illness are on the rise, currently affecting 6%–27% of individuals across populations [89], monitoring subjective satisfaction in relation to lifestyles becomes increasingly important. Longitudinal case studies which consider contextual information will enable a closer look into the expected relationships between social practices and well-being [41].

Deriving insights from cross-sectional analyses assumes 'modernization pathways', meaning that nations develop by following similar pathways, paved by economic and technological progress [34, 80, 90]. Although this assumption has been supported by longitudinal studies on societal transitions [13, 34, 38, 41, 61], some outlying nations achieve high human development at a fraction of the resources required by wealthy nations [24, 26, 34, 90]. We also find that energy and carbon footprints yield similar results, but this might no longer hold in a low-carbon energy future. Future empirical studies could expand by including more nations and testing other environmental indicators such as water or land footprints [24].

Comparing countries through subjective indicators conveys the caveats of cross-cultural analysis [91]. However, data on subjective indicators are increasingly robust and have proven useful [19, 24, 61], as demonstrated by finding different but consistent patterns for objective and subjective satisfaction. While we treat indicators of need satisfaction as independent, some of them are correlated, as we discuss in length in SI4 [3, 5, 19] e.g. better health correlates with living standard. However, we do not investigate the effects of specific goods on QOL nor the efficiency of different market and non-market strategies to satisfy human needs [14, 24]. This remains a key task for future analyses. In SI6 we discuss in detail the validity of our analysis, indicators, limitations, and suggestions for improvement.

Conclusion

At a national level, increasing material consumption entails increasing environmental impact but not necessarily increased QOL. The 'treadmills of production' theory fits our findings of threshold relationships for most objective QOL-carbon footprint relationships, but not for subjective satisfaction. Even if decent material standards tend to be a prerequisite for subjective satisfaction [39, 50], they are not a guarantee [19]. Presumably, consumption has a finite contribution to QOL and once exhausted, satisfaction depends on non-material satisfiers or factors of human ecology [3, 6].

By linking consumption-based footprints and satisfaction through a comprehensive human needs framework [2], we find a richer picture than previously identified through aggregated indicators of QOL [12, 28, 34, 36, 41]. Our conclusion, thus, supports a need-centric approach to sustainability and QOL-impact relationships. The case of *protection* merits special attention, as it drives one fifth of global emissions and yet remains unsatisfied in most dimensions. On the other hand, the general lack of trend between carbon footprint and subjective satisfaction implies the challenge of creating direct low-impact satisfiers. Policy strategies that measure and prioritize human needs would incentivize satisfiers with attractive 'return on investments' in terms of QOL per resource inputs. Through this approach, decoupling the satisfaction of fundamental human needs from environmental damage might become an attainable goal.

Acknowledgments

We thank Kam Sripada and Angela McLean for their editorial assistance. We thank Christian Klöckner for helpful discussions on psychological concepts and statistical methods. We thank the anonymous reviewers for their constructive comments. This work was partially funded by the DESIRE project financed by the European Union's seventh framework program (contract 308552). EXIOBASE3 was constructed in the CREEA project, financed by the same program (contract 265134).

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PAPER II

Sustainable lifestyle scenarios to curb European environmental impact: *Connecting local visions to global consequences.*

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Sustainable lifestyle scenarios to curb European environmental impact: Connecting local visions to global consequences.

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Keywords: sustainable lifestyles, backcasting scenarios, mixed methods, Environmentally-Extended Multiregional Input-Output (EE-MRIO), environmental footprints, water, land, toxicity, carbon, sufficiency, green consumption.

Sustainable lifestyles are at the core of the United Nations' Sustainable Consumption and Production development goal. Upscaling sustainable lifestyles requires citizens' engagement and approval. However, policy efforts would support those lifestyles changes with the best environmental outcomes. .Through backcasting workshops, we compiled stakeholders' visions of sustainable lifestyles in Europe and used them to build 19 scenarios of sufficiency (net reductions) and 17 of green consumption (shift in consumption patterns). We applied Environmentally Extended Input-Output analysis to estimate the scenarios' implications for land, water, carbon and human toxicity and explored synergies and trade-offs across footprints. We also considered issues of global justice by tracing the share of impacts in foreign countries due to European consumption. Overall, we find encouraging environmental outcomes from the envisioned lifestyle scenarios. Switching towards locally sourced, peer-to-peer and community services could mitigate 3-23 % of European environmental impacts. Reducing transport needs, working from home and switching to cycling and walking are options that do not present trade-offs and could mitigate 9-26% of carbon and 2-4% of land and water impacts. Switching to plant based diets has the potential to mitigate between 4-15% across footprints, while reducing food waste and surplus could reduce 2-5% of carbon and save up to 16% of water.

Switching the fibers used in clothing has negligible effects, but making clothes last longer (e.g., through swapping and repairing) could lead to 2% reduction in European impacts. Similarly, sharing and repairing household appliances and devices could yield a 2.5-6% impact reduction s Finally, adopting *passive house* standards or deploying decentralized renewable energy systems show no-trade offs risks and could reduce 5-14% of European impacts. Beyond evaluating scenarios, we present a framework to integrate citizens' visions on sustainability into comprehensive quantitative modelling. Understanding the global consequences of local collective action is key to direct society-wide efforts towards genuine sustainable living.

Introduction

Sustainable lifestyles can be broadly defined as "living good within earth's limits"[1,2]. Encouraging sustainable lifestyles is a central strategy towards the UN's Development Goal of "Sustainable Consumption and Production"[3]. This goal stems from recognizing that the global environmental crisis is ultimately driven by our resource-intensive needs and wants[4–7] –beyond mere population numbers[5,6].

Europeans live some of the worlds' most unsustainable lifestyles precisely due to the large environmental impact embodied in their consumption[8,9]. Depending on the level of consumption and living standards, European households emit between 5 to 20 t CO_2 per capita/yr[9]. Only 20% of those emissions are related to household fuels, while most emissions are embodied in consumer products and services[8,9]. Further, Europe is a net importer of resources and GHG emissions with about half of the impact occurring abroad, often in less wealthy countries[10].

Most attention to lower European impact is given to supply-side solutions, including cleaner production[11,12], renewable energy[13], efficiency[12,14] and circularity[15]. Nevertheless, consumption and lifestyle changes are indispensable for Europeans to reach sustainable lifestyles[11].

Demand-side solutions enabling sustainable lifestyles

Recent efforts explore demand-side options for reducing consumption (**sufficiency**) or consuming less polluting goods (**green consumption**)[11,16–20]. Most studies point to plant-based diets, conserving energy, curtailing travel and living car-free as the most promising actions to reduce impact while enhancing human well-being[16–23].

Because lifestyles are embedded in daily practices, including the things we do, how we spend our time and what we consume[24,257,24–26], they are not entirely a matter of choice[26,27]. Instead, they are influenced by personal features (e.g., worldviews, religion, capabilities)[7,25], socio-economic status (e.g., income, age)[9,21], contextual variables (e.g., climate, political regime)[9,21,26], and constrained by institutions, infrastructures and social practices[26,28,29].

Demand-side policies aim to incentivize sustainable lifestyles through behavioral 'nudges' and infrastructures that encourage low-impact choices[29,30]. However, the whole spectrum, scale and effectiveness of demand-side solutions remains understudied[30]. A broader perspective would include radical lifestyles changes, typically founded on needs-centered views on well-being[7], new social norms[31], grassroots innovations[32], shared economies[33] and others (see [27,30,34,35]).

Unlike top-down deployment of low-carbon technologies or economic instruments[36,37], policies for lifestyle changes require of citizens' engagement and approval in order to succeed[38,39]. Even benevolent top-down policies that do not resonate with the target group are bound to generate resistance, be costly or even create social distress[40]. Further, non-participative public planning restricts the communities' role in launching initiatives to tackle social and environmental challenges[38,40].

Participatory and economy-wide modelling for scenario assessment

Backcasting is a participatory process suitable to embed citizens' views into decision making[41–43]. It literally means "looking back from the future" and consists of collectively envisioning a desirable future and envisioning paths forward to get there[44]. Planning through backcasting has proven to smoothen tensions between top-down policies and the actual needs of citizens[41,43].

Participatory modelling has gained popularity, with the long-overdue recognition that involving stakeholders is key in addressing socio-ecological issues[45–47].- The challenge is to find a balanced tool that is supportive of, and supported by, stakeholders while providing comprehensive and transparent insights of the implications of different pathways[46].

In this paper, we expand the spectrum of options for sustainable lifestyles while involving stakeholders' views. Through backcasting workshops, we compiled visions of sustainable lifestyles produced by European citizens, sustainability frontrunners, public managers, and other stakeholders[42,48]. We then translated the qualitative scenarios into an Environmentally-Extended Multiregional Input-Output (EE-MRIO) framework, which made it possible to systematically quantify and compare the environmental implications of a range of sufficiency and green consumption scenarios.

Studies on demand-side options often vary in scope and methods, hindering comparisons or meta-studies[16,49,50]. Assessing options through a consistent economy-wide model allows for: 1) Considering global supply-chains and trade, 2) Aggregate effects at the European level while isolating household potential 3) Product granularity to build specific scenarios 4) Comparison between scenarios and with respect to status-quo baseline 5) Multi-criteria assessment of trade-offs and synergies by comparing multiple resource and emission footprints.

Predicting the global impacts of the sustainable lifestyle scenarios is not a trivial task in todays' globalized and complex economy. Will upscaling the envisioned changes actually yield the intended environmental benefits? We use EXIOBASE[51], a state of the art EE-MRIO to evaluate the scenarios' potential to mitigate footprints of land, water, carbon and human toxicity. In this way, we propose a multi-indicator life-cycle perspective to identify potentials and pitfalls of scientifically assessed and stakeholder-inspired, pathways towards sustainability.

Method: Environmental Assessment of alternative consumption scenarios

Figure 1 summarizes the procedure and methods used in this research. We conducted backcasting workshops where stakeholders described visions of sustainable lifestyles. We then identified the visions that imply alternative consumption scenarios and the goods that would need to change or reduce in each scenario. We use the backcasting information to parameterize our model in terms of whether the changes occur only in household consumption, or also in production recipes and which is their adoption rate. We then simulate the scenario as a "shock" with economy-wide effects[52]. Finally, we calculated the environmental consequences and compared them to current European impact in order to determine the potential of realizing such scenario.

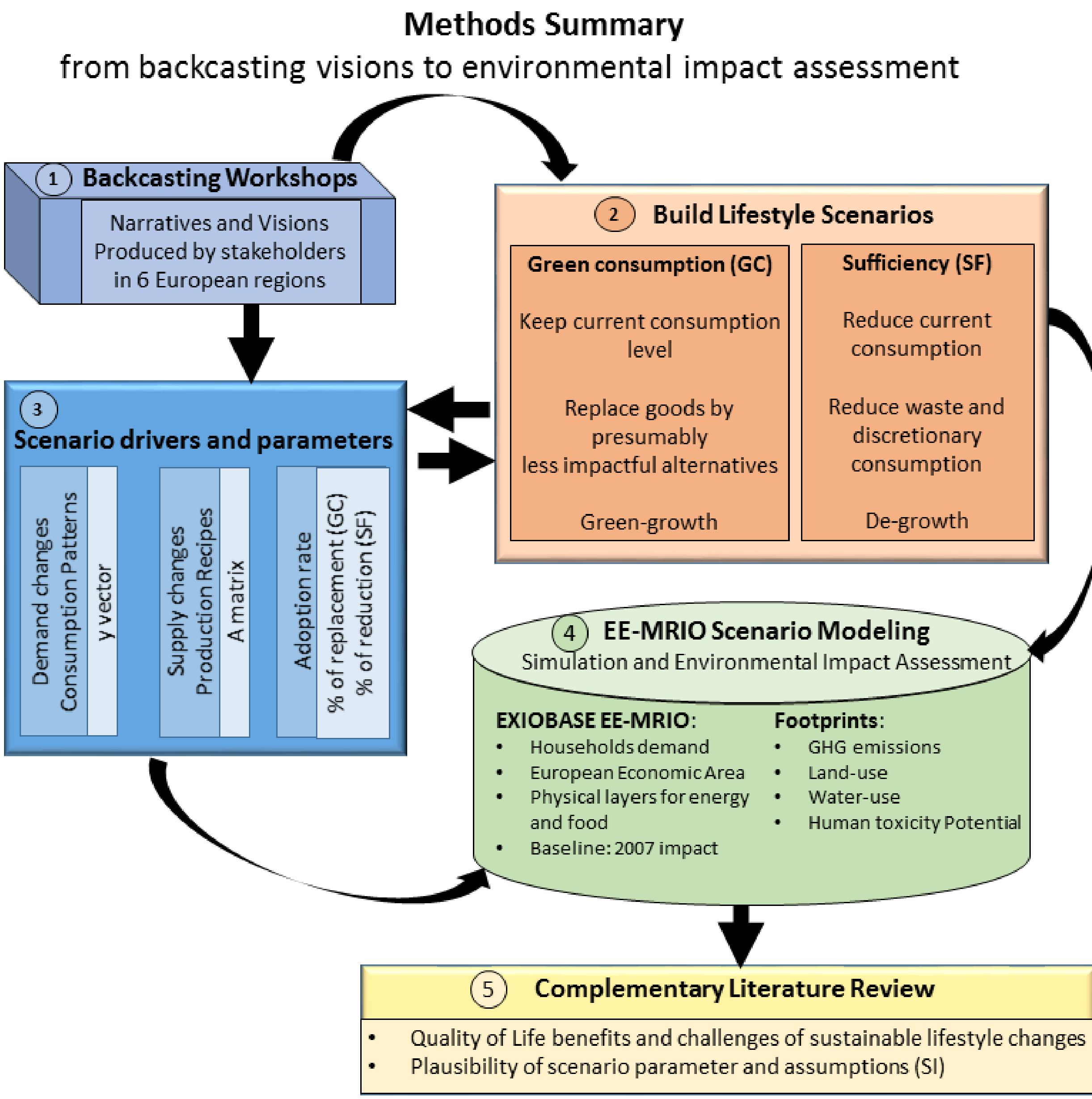

Figure 1 Schematic illustration of steps and framework to model the environmental impact of envisioned consumption scenarios from backcasting workshops. More detail on the steps to translate from qualitative backcasting to quantitative scenarios available in the Supplementary Information (SI).

From backcasting visions to changes in consumption patterns

The data to build consumption scenarios derives from the project GLAMURS, an interdisciplinary research project on sustainable lifestyles[24]. Backcasting workshops were conducted in the regions of Banat Timis, Romania; Halle, Germany; Danube-Bohemian Forest, Austria; Galicia, Spain; Lazio and Rome, Italy; and the Rotterdam-Delft-The Hague metropolitan region, the Netherlands[42]. During the workshops, stakeholders from different societal spheres discussed visions for a sustainable future, including preferred lifestyles changes. Details about the backcasting workshops can be found in the documentation of the GLAMURS project[24,42,48].

The GLAMURS project utilized backcasting as a workshop tool in which relevant stakeholders gather and discuss visions of future scenarios. In the first series of workshops, visions or normative scenarios for sustainable lifestyles were developed for each study region[48]. In the second series of workshops, the emphasis was on assessing and complementing the backcasting scenarios by defining pathways towards the established visions[42]. Finally, we classified the generated visions and pathways as sufficiency or green consumption, according to the following criteria:

Sufficiency scenarios represent lifestyles that seek to reduce material consumption and aspire to a higher quality of life[34]. Sufficiency assumes that once basic needs are satisfied, well-being relies more on health, social relationships, time affluence, and other factors[2,7]. Sufficiency lifestyles are supported by the proposal of voluntary simplicity[34] and align with alternative economic models such as de-growth or steady state[53–55]. By contrast, **green consumption** stands here for consumption that relates to "green growth" economic models[56]. The main assumption is that economic growth may be compatible with the environment through technological improvement directed towards eco-efficiency and circular economy[27]. Green consumption options rely on clean technologies (e.g., renewable energies, bio-economy), and reducing waste by closing material cycles as much as possible through extending lifetimes, re-use, retrofit, remanufacturing, and recycling[57]. Under this vision, people aspire to a sustainable use of resources without needing to change current activities and economic practices in a fundamental way[27].

We scanned the backcasting reports in search of textual statements proposing consumption changes and classified them according to their consumption category (e.g., food, transport, etc.). We further identified whether the vision corresponds to a sufficiency scenario – implying net reductions in consumption– or green consumption –implying consuming differently. We interpreted the visions statements as literally as possible to set up consumption scenarios by identifying the goods and services that would decrease, increase or substitute each other. For example, to model scenarios based on statements such as "clothes will be produced locally and with low transport," we reduced transportation requirements of the clothing sectors ("*Local Clothing*") and quantified the environmental consequences. Text excerpts from the backcasting reports that were used to build scenarios are provided in Supplementary Information (SI).

Footprints and Database

We use an environmentally-extended input-output framework[8,52] to calculate the current environmental pressures of European consumption as a baseline (year 2007), and then compare it with the resulting footprints from the modelled scenarios. Environmental footprint, **fp**, represents the total consumption impacts from European households. We calculate **fp** as a function of household demand, $\boldsymbol{y}$, as follows:

$$\mathbf{fp} = \mathbf{s}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} + \boldsymbol{dhe} \qquad (1)$$

where $\boldsymbol{s}$ is the coefficient vector resulting from dividing the total resource or emission required for the production of a given good by its economic output (e.g. CO_2/EUR), **I** is the identity matrix and **A** is the technical coefficient matrix, representing the inter-industry requirements. The $\boldsymbol{dhe}$ vector represents direct household emissions from the combustion of fuels for transport, cooking and heating.

Our modelling is based on EXIOBASE2, an Environmentally Extended Multiregional Input-Output (EE-MRIO)[58] database. EXIOBASE2 represents the production and consumption of 200 economic goods for 43 countries and 5 rest-of-world regions for the year 2007. Satellite accounts for resources and emissions are available for each sector and country. For each footprint, we consider the resources and pollutants in **Table 1**. Our unit of analysis is the final demand of households of the European Economic Area, hereafter referred as Europe. See SI for details on countries included and EXIOBASE2 coverage.

Table 1 Environmental footprints, including factors of productions and chemicals covered.

Footprint	Coverage	Unit
Carbon Footprint	Global Warming Potential of CO_2, CH_4, N_2O (combustion and non-combustion) and SF_6. Includes direct household emissions (GWP 100, IPCC 2007).	Mt CO_2 equivalent
Human Toxicity Potential	NOx, NH_3, dioxins (PCDD_F),HCB, PM10, As, Cd, Cr, Cu, Hg, Ni, Pb, Se, Zn and SO_x (combustion and non-combustion). Non baseline characterization factors (CML, 2001)[59].	Mt 1,4-dichlorobenzene-equivalent
Land Footprint	Total land use: forests, pastures and arable land	M km^2
Water Footprint	Total blue water consumption. Includes direct household water consumption.	Km^3

Table 2 shows the impact intensity per euro spent for detailed consumption categories. Food is the most water and land intensive category, while mobility and shelter are the most carbon intensive[8]. Transport emits the most human toxins per euro, while services have a relatively impacts per EUR. Table 2 will serve as a baseline to interpret the scenario modelling results.

Table 2 Average intensities in impact per euro for consumption categories. Calculated as footprint of each product category divided by the total consumption of that category aggregated for Europe. DCB: dichlorobenzene. Own calculation based on EXIOBASE[51]. Calculations of energy per kilo for food and fuels can be found in the SD.

European environmental intensity of consumption						
	Carbon (kg CO_2 eq/EUR)	Human Toxicity Potential (kg 1,4-DCB eq/EUR)	Land (m^2/EUR)	Land (m^2/kg)	Water (liter/EUR)	Water (liter/kg)
Clothing and apparel	0.79	0.70	1.70		31.79	
Construction materials and work	0.75	0.49	3.29		8.27	
Food: processed	1.11	0.62	3.61	10	118.92	333
Food: Dairy	1.45	0.62	4.70	13	80.49	222
Food: Meat and fish	1.44	0.65	3.63	76	94.67	1972
Food: Plant-based	1.35	0.44	7.81	19	292.80	712
Manufactured products: Appliances, machinery and electronics	0.70	0.71	0.51		8.44	
Manufactured products: Media and communication apparatus	0.55	0.57	0.88		9.15	
Manufactured products: Plastic, paper	3.44	4.19	1.38		41.85	
Transport: By air	2.01	0.77	0.38		6.98	
Transport: By land	2.04	0.94	0.49		8.72	
Transport: By water	3.09	122.28	0.48		9.05	
Services: Information technology	0.37	0.30	0.35		5.07	
Services: Business and financial	0.19	0.16	0.17		2.78	

Services: Health, education and research	0.28	0.23	0.47	8.84
Services: Renting services and real estate	0.18	0.16	0.19	2.30
Services: Recreation and tourism	0.50	0.58	0.97	25.30
Services: Trade and retail	0.39	0.54	0.48	8.90
Housing: Electricity and fuels	4.46	0.66	1.89	12.18
Housing: Household commodities	1.06	0.70	2.23	16.76
Housing: Recycling	1.09	1.10	0.48	7.28
Housing: Waste treatment	1.16	0.40	0.39	6.67

Modelling consumption changes with EE-MRIO

The global EE-MRIO described above accounts for different production recipes, trade supply chains and household consumption patterns across nations. The basis of the model to simulate backcasting scenarios is to perturb the EE-MRIO by modifying the consumption patterns in the **y** vector or production recipes in the **A** industry matrix[52]. The magnitude of the perturbations follow the uptake rates stated in Table 3.

The full mathematical model to simulate changes in consumption using an EE-MRIO has been adopted from Wood et al. and can be consulted in detail elsewhere[52]. Here we limit to model visions of alternative consumption patterns in households (**y** vector of final demand per product), and/or changes in industrial practices (**A** matrix of technical coefficients). We model three types of scenarios[52]:

1. Change in households' demand (Change in **y**): Either a reduction in consumption or consuming different goods. In both cases, the scenario modelling consists of simulating a demand change in the relevant goods.
2. Change in industries' demand (Change in **A**): When the envisioned scenario depends on changes in inter-industries production recipes and inputs. For example, to produce *Organic Food* implies reducing the inputs of agrochemicals to agricultural sectors.
3. Change at both households' and industries' demand (Change in **A** and **y**): Some scenarios entail simultaneous changes in household demand and industrial practices. For example, adopting vegetarian diets will imply that households reduce their

purchase of meat directly (**y**) but also that restaurants have less demand for meat products (**A**).

While sufficiency scenarios imply a net reduction in the consumption of specific goods, green consumption scenarios imply that the reduced consumption of one product (*i*) is substituted by increasing the demand of another product (*g).* As substitute products may differ in price or energy content per functional unit, the extent of replacement is affected by the relative differences p between the products, with no differences having a unitary value.

Expenditure is kept as the monetary functional unit for most services and aggregated product categories, as no physical layer could be derived. The original model allows for price differences in product substitutes but does not explicitly consider the physical utility delivered by goods (e.g., energy use, calories provided)[52]. In this research, we enhance the model by introducing a physical layer to balance food and energy goods.

For food and energy, which make up nearly half of the EXIOBASE2 goods, prices underlying the EXIOBASE2 model[51] were used to convert to mass or volume. Further, data on energy content was applied in order to convert to physical functional units i.e. kcal or TJ by weight in kilo- grams (or by volume in m^3), as explained in the SI and data file. Deriving physical functional units allows us to introduce the current living standards as a constraint by keeping the same level of nutrition (kcal) or energy use (kWh) while shifting the means of provision, as proposed by green consumption scenarios.

The differences in prices or energy content per kilogram of fuels and food that modulate product substitution are modelled as follows:

$$p = \frac{p_g}{p_i} \qquad (2)$$

Where $\boldsymbol{p}$ determines the proportion of expenditure shifted in a given scenario. For example, a value of 0.5 would mean 50% of the expenditure of reduced products, $\boldsymbol{i}$ is shifted to increased products, $\boldsymbol{g}$. This would be the case if a substitute energy carrier delivered twice as dense as the current i.e. double energy per weight. For monetary layers, an example would be buying textiles for do-it-yourself clothes is five times cheaper than in-store apparel i.e. $\boldsymbol{p} \approx 0.2$. Differences in price and energy densities modulate the substitution share in products demanded by households and industries alike[52].

While differences in energy densities are modelled for all food and energy, prices differences between substitute goods modelled in monetary terms were rarely assumed, reported in the "price deflator" row in the of the Supplementary Data modelling parameters. Differentiating price and quality between comparable goods is limited by the product aggregation in EE-MRIO analysis[60]

Table 3 is a full account of the envisioned consumption scenarios modelled in this paper. The "visions" column describes the actions to achieve sustainable lifestyles articulated by the backcasting workshops participants. The "description" column summarizes the statements from the reports[42,48]. The "modelled changes" column represents the translation from qualitative statements into the modelling decisions that best represent the envisioned scenario. We classified the scenarios as sufficiency (SF) or green consumption (GC) according to the aforementioned criteria. The values under **y** and **A** indicate the assumed uptake by households and industries, respectively. Since our goal is to understand the possible environmental outcomes of scaling up the envisioned lifestyles, we assumed aggressive uptake rates to reflect a maximum potential. However, we consider technical or physical limitations when relevant (i.e., food waste cannot be totally eliminated, minimum daily caloric intake[6], etc.). Assumptions are detailed in the SI. When pertinent, we model "sensitivity scenarios" to provide an opposite case for comparison. For example, we model *Industrial Materials* as a contrast to a scenario of building with *Natural Materials*. Sensitivity scenarios, however, do not represent stakeholders' visions.

It should be noted that scenarios of either reduced consumption or reduced inputs to production are applied directly and thus imply a reduction in the GDP of the economy, given that all other variables remain constant (see discussion and limitations). In the discussion we consider economic challenges and quality of life benefits associated with the scenarios. In the SI, we characterize the the sensitivity of considering an economic rebound effect for the scenarios that represent monetary savings

Table 3 Scenarios built from backcasting visions. The values for y and A parameters indicate the assumed adoption level in household demand or inter-industry demand, where the value indicates the degree of substitution in the case of green consumption e.g. 1 is full substitution of products. For sufficiency, the value indicates the level of reduction, where 1 symbolizes a total ban of a given product. (see SI for details on assumptions). Visions marked with * are modelled through physical balances and baseline energy (kcal or kWh) are introduced as a constraint to be kept constant. ***Interpretation Key: Animal free clothing proposes a vegan fashion industry, which imply replacing animal textiles with plant-based textiles. This is classified as green consumption (GC) because it keeps clothing consumption constant but with different, presumably more sustainable, materials. The adoption rate is full (y = 1, A=1) because it implies a total ban of animal textiles both in household consumption and in industrial recipes.***

	Visions	Description	Modelled changes in consumption	SF/GC	y	A
Clothing	Animal Free	No clothing of animal origin (vegan clothing).	Substitute wool, furs, leather, and replace with textiles/plant-based fibers.	GC	1	1
	Durable Fashion	Reduces textile consumption e.g., clothes swap, second hand use, repairs	Reduces clothes and wearing apparel by 80%. Shift 20% of spending by textile materials (fibers and wool) and leather.	SF	0.8	0
	Natural Fibres	No petroleum-based clothes. Only natural fibres, e.g., wool, fur, cotton	Replace plastic/rubber inputs to clothing sectors with natural fibres by 90%.	GC	0	0.9
	Local Clothing	Only local clothing clothes and fibers.	Reduce by 50% the transport inputs to sectors of clothing and apparel.	SF	0	0.5
Construction	Minimum Construction work	Minimal construction due to large scale co-habitation and downsizing. Only minimal repairs and renovation takes place.	Reduce all construction work and materials by 90%	SF	0.9	0.9
	Repair Renovate	Intensive refurbishment and renovation of existing residential buildings.	Shift 5% of all overall expenditure (except for food) to increase construction work and building materials.	GC	0.5	0.9
	Natural Materials	Building with natural construction materials: wood, clay, stone and sand.	90% decrease in cement, bitumen, metals and foundry work. Increase in wood, clay, sand, stone and non-metallic mineral products.	GC	0.9	0.9
	Industrial Materials	Building and renovation with industrial materials: concrete and metals	Reduce wood, clay, sand, stone and non-metallic mineral products. 90%. Increase in concrete and metals.	SS	0.9	0.9
Food - Diet	Processed Food*	Shift towards more processed food and ready to eat food products.	Reduce all raw and plant-based foods, as well as live animals, by 80%. Replace with processed food products.	SS	0.8	0
	Food Sufficiency*	Limits food consumption to 2586 kcal/day. Reduces food surplus.	Reduce all food product spending by 27% (corresponding to surplus calories).	SF	0.27	0
	Mediterranean Diet*	High consumption of plant-based food, fish, dairy, and wine. Less meat.	Decrease non-fish meat products by 80%, increase all others foodstuff. Hotels and restaurants (H/R) change their inputs.	GC	0.8	0.8
	Vegetarian*	Vegetarian food with dairy and eggs but no meat.	Reduce meat and fish to 100%. Replace with plant-based food, diary, and processed food. Hotels and restaurants change their inputs.	GC	1	1
	Vegan*	Vegan food (no red/white meat, eggs, or dairy products).	Eliminates all food animal products. Increase all other food. Hotels and restaurants change their inputs.	GC	1	1
	Healthy Vegan*	Vegan food and eliminates processed foods, sugars and beverages.	Eliminates all food animal products, processed food, sugar and beverages. Hotels and restaurants change their inputs.	GC	1	1
Food SC	Local Food	Shift towards locally sourced food, including hotel/restaurant sector.	Reduce transport needs of food industries by 50%.	SF	0	0.5
	Organic Food	Food and animals are produced without agrochemicals.	Reduce fertilizers, chemicals and medicines as inputs to food and H/R products by 100%.	SF	0	1
	Seasonal Food	Less vegetables grown in greenhouses through seasonal consumption	Reduce inputs of fuels and electricity to vegetable sector by 30%.	SF	0	0.3
	Less Waste	Reduce food waste at the household level.	Reduce all food product spending by 12%[61] (corresponding to estimated calories that currently go to waste).	SF	0.12	0
Man. products	Share & Repair	Collaborative ownership of appliances and tools. Second-hand buying/renting, tool library and repair cafés. Shift to services.	Reduced consumption of machinery and electronic apparatus and their retail/trade by 50%. 10% of expenditure shifts go to renting apparatus.	GC	0.5	0
	Offline Minimalist	Less media, Internet, telecommunication equipment etc.	80% reduction of media, machinery, electric apparatus, telecommunication devices and services related.	SF	0.8	0
	Durable appliances	Extended appliance lifetime, increased reparability lowers consumption	80% reduction of general appliances, office equipment devices and precision instruments.	SF	0.8	0
	No Chemicals &Plastics	Reduces use of chemicals and plastic, e.g., bottled beverages, plastic bags	90% reduction of chemicals, fertilizers, cleaning agents, plastics and rubbers at the household.	SF	0.9	0
Mobility	Frequent Flyer	Flies frequently.	Reallocate 2% of all product spending, except on food, towards air transport.	SS	0.02	0
	Cycling & Flying	Cycling increases, reducing land transport but people fly with the savings.	50% reduction of products related to local land mobility, shifting expenditure to air mobility.	GC	0.5	0
	No Flying	Stops flying.	Eliminates all air transport services.	GC	1	0
	Renewable Fuels	Public transport and private vehicles use mostly liquid biofuels.	Substitute 90% of all fossil transport fuels by bio gasoline, biodiesel, ethanol fuels and others. Including direct household mobility. Inputs to land transport services and motor fuel retail industry shift towards biofuels.	GC	0.9	0.9
	Less Cars (50%)	Expanded public transport, car co-ownership and ride share are deployed.	Substitutes 50% of income spent on private vehicles and fuels with land public transportation (bus, train, metro, etc.).	GC	0.5	0
	Less Transport (50%)	Overall decreased mobility, e.g., through digital lifestyles and efficient cities	50% reduction of all products related to mobility.	SF	0.5	0
	Work from Home (50%)	Reduces need for mobility by working from home, living close to work, etc.	Reduces spending on mobility by land by 50%.	SF	0.5	0
	Work from Home (50%) ER	Same as "Work from Home" but ER assumes that more time spent at the home could increase electricity and heating needs..	Reduces spending on mobility by land by 50%, increase electricity and heating fuel spending by 20%.	SF	0.5	0
	Bike Walk Full	Bikes/walks everywhere for land commute. Other mobility constant.	100% reduction of vehicles, fuels and services related to mobility by land.	SF	1	0
Services	Leisure Services	Increased travel agencies, restaurant food, spa, entertainment, etc. Focus on hedonism and disregards insurances and financial security.	80% reduction expenditure in health, education and financial services and instead spends on entertainment, tourism, hotels and restaurant and shopping.	SS	0.8	0
	Non-Market Services	Large-scale collaborative economy and inter-community exchanges, voluntary work, time banks and community services.	80% lower use of all services.	SF	0.8	0
	Community Services	Engaged in recreational, sport and cultural organizations, high communication	Decrease leisure services and tourism by 80%, substitutes with recreational and membership organization services.	GC	0.8	0
	Local Services	Local and decentralized service supply. Local economy favors servicing.	Reduce direct household spending on local mobility by 20%[25]. Reduce transport inputs into all services by 30%.	SF	0.2	0.3
Shelter	100 % Fossil Fuels*	Replaces household renewable fuels and electricity with fossil fuels	Full replacement of current renewable electricity and energy with fossil sources.	SS	1	0
	Renewable Electricity*	Renewable electricity by wind, photovoltaic, solar, geothermal and tidal.	Reduce fossil electricity by 100%, replace with renewable electricity.	GC	1	0
	Passive housing	Passive house standard and energy-efficient dwellings.	Reduce energy spending by 43%[62] (i.e. 40% lower energy need). Shifts 20% of consumption to construction work and insulation.	GC	0.43	0
	No energy Ecovillage	Models a pre-industrial energy use while keeping all else constant.	Decrease spending on energy carriers and grid services by 100%. Models the impacts of current electricity and fuel consumption.	SF	1	0
	High-tech Ecovillage	Decentralized, local, small-scale renewable energy production distributed through micro grids.	Decrease spending on fossil based electricity and overall transmission grid services. Substitute with local generation of renewable electricity: solar, hydro, wind, geothermal. All other fossil fuels for heating remain the same.	GC	1	0
	Water Off-Grid	No conventional water distribution. Water use from natural sources.	100% reduced expenditure on collected and purified water, distribution services of water.	SF	1	0

SF= sufficiency (net reduction), GC= Green consumption (shift in consumption), SS= Sensitivity Scenario, ER = Energy Rebound,

Results

Environmental impact assessments of lifestyle visions

Table 4 summarizes the impact assessments for the envisioned scenarios of green consumption and sufficiency. **Sufficiency** options have higher mitigation potential in the domains of transport, services and clothing, while **green consumption** options are more attractive in the domains of food and manufactured products. We find that large-scale shifts towards plant-based diets, reductions in motorized transport and energy-efficient housing offer the most potential to curb European environmental impacts[18]. Reducing manufactured products and clothing hold considerable potential, above 2% across footprints.

While here we contrast green consumption and sufficiency, in practice some of these actions might be complementary. For example, adopting plant-based diets does not exclude preventing food waste or eating organic. For green consumption options, however, the environmental impact of the alternative goods and the volume of consumption, will largely determine the environmental outcome, e.g., the foods chosen to replace meat in diets[63].

We mark footprint changes below 2% in yellow to signal uncertain outcome, where the observed change is relatively small and the practical implementation of such scenario could tip the balance towards reduction or increase. Energy and food scenarios were modelled through a physical energy layers (marked with * in Figure 2 and Table 3) in order to maintain current energy demand (kcal or kWh) and model the isolated effect of shifting food and energy carriers (such as in *Renewable Electricity* or *Vegetarian.)*. See SI for modelling of physical layers.

Table 4: Environmental synergies and trade-offs of green consumption and sufficiency scenarios. Mitigation potential (green and positive) or backfire (red and negative) expressed as a percent difference (Δ) with respect to the baseline. Color-coding as follows: yellow: Δ ±2%; light red: Δ < -2%; dark red: Δ <-5%; light green: Δ >2%; dark green: Δ >5%. Yellow color represents small and thus uncertain results. The outcome of these actions would depend on their practical implementation. The values summarize the percentages reported in Figure 2.

Consumption domain	Green Consumption Scenarios	Mitigation potential				Sufficiency Scenarios	Mitigation potential			
		Carbon	Toxicity	Land	Water		Carbon	Toxicity	Land	Water
Clothing	Animal Free (Ctrl)	-0.8%	-0.5%	-1.2%	-0.5%	Local Clothing	0.5%	1.7%	0.3%	0.5%
	Natural Fibers	0.0%	-0.1%	-0.3%	-0.3%	Durable fashion	1.8%	2.5%	2.1%	2.1%
Construction	Repair & Renovate	-0.7%	2.4%	-10.8%	1.0%	Minimum Construction	1.8%	1.3%	3.5%	0.5%
	Natural Materials	0.5%	0.1%	-1.4%	0.0%	Work				
Food	Mediterrenean Diet*	2.7%	0.2%	-0.1%	-0.5%	Food Sufficiency* (Ctrl)	4.9%	2.6%	14.4%	16.0%
	Vegetarian*	6.4%	3.0%	0.6%	0.2%	Local Food	0.6%	3.6%	0.1%	0.1%
	Vegan*	13.9%	9.0%	4.7%	14.8%	Organic Food	1.8%	1.0%	0.8%	1.3%
	Healthy Vegan*	15.7%	12.0%	-2.9%	9.7%	Seasonal Food	0.1%	0.0%	0.0%	0.0%
						Less Waste	2.1%	1.1%	5.5%	7.1%
Manufactured Products	Share Repair	4.3%	6.2%	2.7%	2.5%	Less Chemicals & Plastics	3.9%	4.0%	2.7%	4.4%
						Offline minimalist	1.5%	2.0%	0.6%	0.6%
						Durable Appliances	1.5%	2.0%	1.0%	0.7%
Transport	Less Cars (50%)	8.8%	1.7%	0.8%	0.6%	Less Transport (50%)	14.5%	20.4%	2.0%	1.9%
	Renewable Fuels	12.1%	1.4%	-5.9%	-5.3%	Work from Home (50%)	13.0%	7.1%	1.9%	1.8%
	No Flying	2.3%	1.0%	0.3%	0.2%	Work from Home (50%) ER	8.9%	6.1%	-1.0%	1.2%
	Cycling & Flying (Ctrl)	0.1%	1.3%	0.3%	0.4%	Only Bike and Walk	26.0%	14.2%	3.8%	3.5%
Services	Community Services	3.1%	23.8%	3.6%	6.6%	Local Services	5.3%	2.9%	0.8%	0.7%
						Non-market Services	17.8%	21.5%	14.6%	15.8%
Housing	High Tech Ecovillage*	7.9%	1.3%	1.7%	0.3%	Low Tech Ecovillage	13.8%	4.9%	4.9%	2.6%
	Renewable Electricity*	2.9%	0.2%	-3.1%	-0.1%	Water Off Grid	0.5%	0.2%	0.1%	0.1%
	Passive House	5.6%	1.9%	5.0%	1.1%					

Overall, we find encouraging environmental outcomes from the envisioned consumption scenarios. Switching towards locally sourced, peer-to-peer and community services could mitigate 3-23 % of European environmental impacts. Reducing transport needs, working from home and switching to cycling and walking are options that do not present trade-offs and could mitigate 9-26% of carbon and 2-4% of land and water impacts. Switching to plant based diets has the potential to mitigate between 4-15% across impacts, while reducing food waste and surplus could reduce 2-5% of carbon and save up to 16% of water.

Switching the fibers used in clothing has negligible effects, but making clothes last longer (e.g., through swapping and repairing) could lead to 2% reduction in European impacts. Similarly, sharing and repairing household appliances and devices could yield a 2.5-6% reduction across impacts. Finally, the outcome of alternative housing would depend on the chosen energy carriers. If forestry products are to supply the current heating and cooking needs, carbon emissions could be reduced by 8%, but at the cost of doubling land requirements. Adopting *passive house* standards or to live at the margins of centralized energy systems show no-trade offs and could reduce 5-14% of European impacts.

The magnitude of our results are not surprising. Previous assessments associate housing, transport and services to 70% of carbon emissions, while food alone takes up half of the water and land embodied in European consumption[8,9]. Clothing, construction, and durable goods together account for about twenty percent of resource use and emissions[8,9]. The following section describes results for each consumption category in detail.

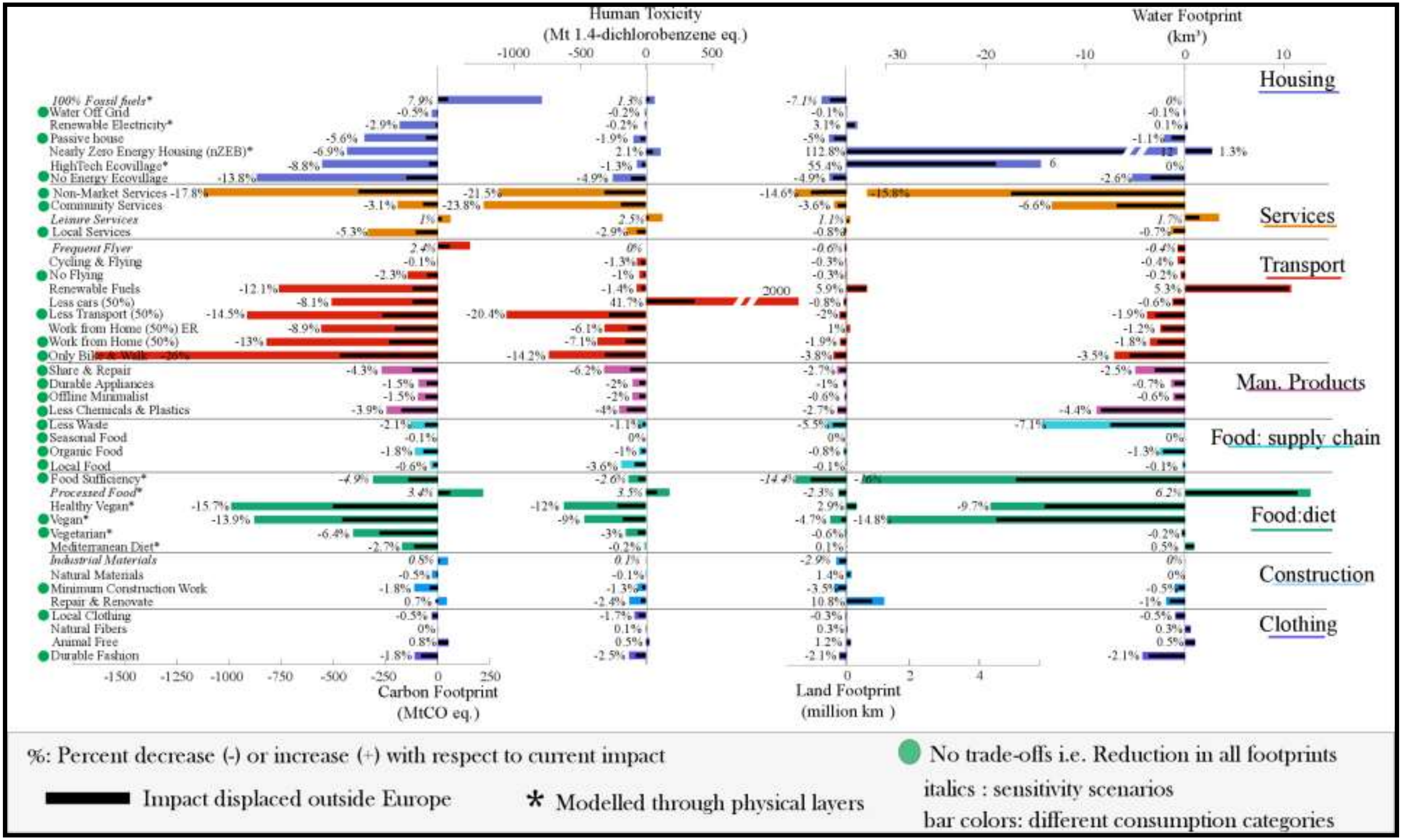

Figure 2 Relative and absolute footprint changes with respect to lifestyle change scenarios. Percent values indicate deviation with respect to baseline footprint of 2007. Black bars show the impact share that occurs outside the European Economic Area. A green dot indicates the consumption changes that present a positive reduction and no trade-offs across footprints to indicate the "safe options." Asterisk * indicates lifestyles modelled through physical energy balances of kcal or kWh. ER=energy rebound (see Table 3). ***Italics*** **indicate sensitivity scenarios, which are stylized by the authors to provide a worse case scenario.**

Clothing

While net reductions in the consumption of clothing and construction may curb impacts, simply shifting materials offers modest reductions with possible trade-offs, as shown in Figure 2. *Durable Fashion* could halve current impact of clothing, reducing the environmental of Europeans by 1.8-2.5% by extending clothes' lifetimes and increasing secondhand re-use. Lowering clothes miles by preferring *Local Clothing* reduces human toxicity by 1.7% due to the high toxicity of transportation fuels (Table 2), with marginal reductions in other footprints (Figure 2). Replacing all synthetic fibers with *Natural Fibers* has a negligible mitigation potential across footprints. Phasing out animal fibers for plant-based and synthetic fibers would require 1.2% more land and 0.5% more water as shown by the *Animal free* clothing scenario. Choosing natural over synthetic clothing materials present negligible carbon reduction potentials with potential increases in other footprints. In sum, only sufficiency scenarios of net reductions in clothing offer mitigation potential.

Construction

Co-habitation and downsizing of living spaces could *Minimize Construction Work*, reducing land and carbon footprints by 3.5 and 1.8%, respectively. Intensive *Repair & Renovation* could increase land use about 11% and slightly reduce other footprints, due to the lower intensity of construction goods with respect to other categories (Table 2). Using more *Natural Materials* in construction results in a carbon reduction of 0.5% but a land increase of 1.4%. *Natural Materials* such as wood, stone, sand and clay require more land but emit less carbon since they require less processing and energy compared to concrete and metals. We model the opposite case in *Industrial Materials* by building with concrete, steel and aluminum. This would decrease land by 3% while increasing carbon footprint by 0.8%. Although construction is not typically associated with lifestyles, 70% of Europeans households own their dwelling[64] and thus can influence the energy efficiency and materials in their houses. Renovation for thermal performance could decrease energy use per area but expansion of current living spaces would have the opposite effect[65].

As with clothing, the choice of natural over synthetic materials in construction shows a negligible potential reduction in carbon, toxicity and water accompanied by potential increase in land. Again, only sufficiency scenarios in construction offer considerable mitigation potential. Noteworthy, wood materials are rather intensive in "forest land", while natural fibers rely mainly on croplands (e.g., cotton) (Table 1).

Food: Diets

All low-meat diets provide significant environmental footprint reductions (Figure 2). A *Mediterranean Diet* would lower non-fish meat and increase legumes, oils, vegetables, cereals, fish and dairy, and could reduce carbon emissions by 2.7% at the cost of a slight increase of land and water. A full *Vegetarian* diet would reduce carbon and toxicity by 6.4 and 3.0%, respectively. Removing dairy products and eggs (*Vegan* lifestyle) yields a reduction potential of carbon (14%) and of toxicity and water footprints of 9 and 15%, respectively. With a *Healthy Vegan* diet (reduced sugar, beverages and other processed food products), the carbon and toxicity footprints would be decreased by 16 and 12%, respectively. The slight land footprint increase for *Healthy Vegan* lies in the low price but relatively high calorie of unhealthy vegan foods such as sugar and beverages. Supplying calories with sugar requires less total land than supplying the same calories with oils and nuts, for example. This result is not conclusive, and in practice the outcome will depend on the food products that constitute a *Healthy Vegan* diet[63].

We model the sensitivity scenario of *Food Sufficiency* by limiting the calorific intake to a sufficient amount for European standards of 2586 kcal/day[2] and find that such measure may reduce the total carbon footprint by 4%, twice the potential found by a prior study of France[66]. *Food Sufficiency* yields a decrease in total agricultural land needed; the water and land footprints may decrease by 16% and 14%, respectively. Our results agree with previous findings that show 20% of European food is supplied in a surplus, which in turn largely drives waste and overeating[67]. The *Processed Food* simulates a higher intake of processed food and lower intake of plant-based and staple foods. This would increase all footprints except land, for a similar reason as discussed above with respect to the *Healthy Vegan*, but also because supplying current caloric needs exclusively through *Processed Food* would come at a greater cost, and thus prevent expenditure in other products (see "physical layers" in SI).

Food: Supply chain

Organic Food could reduce carbon (1.8%), land (0.8%) and water (1.3%) while *Local Food* reduce toxicity footprint (3.6%) due to lower transport needs. The scenario of more *Seasonal Food*, where energy inputs to agriculture reduce by 30%[17], has no significant mitigation potential. Europe consumes a large share of imported food, and agriculture requires relatively low energy inputs. However, in a scenario where a larger share of food is produced within Europe, the effects of seasonal food might be more significant.

We confirm previous findings of *Organic Food* having lower impact than consuming *Local Food* which reduces food miles[68]. However, when we add human toxins to this debate, we find that *Local food* is preferable for reducing toxicity in Europe. Policies to favor synergies between *Organic*, *Seasonal* and *Local* agriculture could lead to dynamic effects that yield potential beyond our estimates[23]. *Less Waste* would imply reduction of food consumption by 12%[61] (1.2% of total household expenditure). Our results agree with previous estimates of at least 2% of European carbon to be food waste[69] and are within the 2-7% range reported by Usubiaga et al, based on Exiobase[70] . Indeed, we find reducing food waste can reduce by 5.5 and 7% the use of land and water, half of it outside Europe.

Combining sustainable diets and supply chains could yield further reductions. A *Vegan* diet with *Less Waste* and *Organic Food* could potentially reduce footprints of up to 18, 11 and 24%, for carbon, land, and water, respectively. Our general findings agree with previous research that reports low-meat diets[16,18,63,71] and organic food[69,72] have lower environmental impact than conventional diets. In sum, we find most reduction potential by shifting to non-meat diets, while reducing food waste and miles yield lower, yet considerable, reduction potentials.

Manufactured products

Share & Repair reduces carbon by 4.3% and toxicity by 6%; assuming increased sharing, reparability, re-use and product-service systems. The scenario of *Durable Appliances* and *Offline Minimalist* show comparable reduction potentials. *Durable Appliances* extends useful lives of appliances while *Offline Minimalist* reduces personal electronic devices and media consumption to offer a reduction of 1.5 and 2% for carbon and toxicity, respectively. A scenario of *Less Chemicals & Plastics* entails lowering household chemicals and plastics, with a 4% reduction potential in carbon. Reducing chemicals reduces the pressures of foreign land and water, while *Share & Repair* has a significant reduction of carbon and toxicity within Europe.

Mobility

Replacing all local land transport with biking and walking (*Only Bike Walk)* can potentially reduce carbon by 26% and toxicity by 14%. *Work from Home* implies mainstreaming flexible and remote work, thereby halving current commutes and reducing carbon and toxicity by 13% and 7%. If *Work from Home* becomes widespread, there is a risk of increased use of fuel and electricity at home. We estimate such possibility in *Work from Home ER* at mitigation potentials of only 9% carbon and 6% toxicity. Such rebound could be counteracted by energy efficient housing or decentralized working spaces that workers can reach without motorized transport.

Similar to others, we find that shifting to public transport is efficient in reducing carbon[18,73]. *Less Transport* implies 50% reduction in all motorized transport, thereby reducing toxicity (20%) and carbon (14%). The *Less Cars* scenario models a large adoption of car-free lifestyles, implying a 50% expenditure shift from private vehicles towards collective transport and shared vehicles. This could reduce carbon up to 8.8% and toxicity by 1.7%. By modelling transport through a top-down MRIO, we do not consider the demand of passenger-kilometers directly. Since 80% of current European commute is done with passenger-cars[74], shifting monetary demand from private to public transport could lead to a surplus of passenger-kilometers, e.g., more buses, trains and ferries. Thus, bottom-up, country-specific data on fleet inventory and passenger-kilometeres by transport mode would increase the accuracy of the model.

Adopting *Renewable Fuels* for mobility potentially decreases carbon (12%) and toxicity (1.4%), with the risk of increasing pressures on foreign land and water by 5.8 and 5.3%. This result stresses the importance of considering consequences abroad in policies such as the EU 2020 energy strategy[37]. *No Flying* could reduce carbon by 2.3% while *Frequent Flyer* could increase carbon by 2.5%. Shifting demand from other goods towards flying frequently would actually reduce the land and water footprint, due to relative low water and land intensity, and high price of air travel, compared to other goods (Table 2). *Cycling and flying* portrays a scenario of commuting by walking, cycling and public transport but flying with the savings. We find that the carbon reductions of active transport would be offset by the rebound effect of flying, with the risk of increasing toxic emissions by 3%. This result suggests that air transport should be discouraged as active transport is encouraged, to prevent a rebound effect.

Services

The *Local Services* scenario portrays a lifestyle that mostly takes place within the neighborhood. It entails a moderate reduction of short distance mobility coupled with preference for locally sourced services that require less transport logistics. Favoring *Local Services* could reduce carbon (5.3%) and toxicity (3%) footprints. The lifestyle of *Community Services* portrays reduced tourism and leisure to be more engaged in recreational, sport and cultural organizations. Citizens would be active in community organization and communications, leading to a reduction of toxicity (24%) and water (6.7%) due to a combined effect of reduced transport needs and shifting toward services with lower impact intensity, such as organizations and club membership.

Non-market Services envisions communities where citizens largely supply each other with services through collaborative economies, voluntary work, time banks and community services, reducing all impacts by 15-20%. However, we do not account for the fresh inputs that a *Non-market Services* would require to maintain the current service levels, which might overestimate the potential. The sensitivity scenario of *Leisure Services* would slightly increase current footprints by shifting expenditure in health and education towards entertainment, tourism, restaurants and shopping.

Even if services are less impactful per euro compared to physical goods (Table 2), their consumption volume makes them relevant for impact mitigation, as shown by *Community Services.* However, this result should be interpreted cautiously as in reality switching to *Non Market Services* would imply economic de-growth and possibly lower incomes, which are macroeconomic effects beyond our scope.

Shelter

Renewable electricity shows that shifting remaining fossil fuels to renewable electricity would lead to increased land and water while decreasing carbon footprint by 3%. We interpret this result with caution, as the scenario assumes the European renewable energy mix for 2007, where hydropower held a major share, but the outcome might be different with larger contributions from solar and wind. Previous findings confirm that large scale hydro-power and biofuels are land and water intensive[13]. Consequently, switching to *100% Fossil Fuel* would decrease land but increase carbon, reflecting the freeing up of land currently used to supply hydropower and biofuels.

Passive Housing could potentially save 6% carbon and 5% land by reducing space heating by 40% through renovating for energy efficient dwellings. The efficiency potential was estimated by comparing current statistics on European space heating needs[75] to the passive house standard (15 kWh/(m^2yr) passive), according to previous approaches[62] (see SI).

A *HighTech Ecovillage* simulates self-sufficient and decentralized renewable electricity generation. This scenario leads to a reduction of 7.9% of carbon and modest reductions between 0.3-1.7% in other footprints. A *HighTech Ecovillage* fits the idea of an urban ecovillage, which reduces the share of fossil fuels and the impact of grid services and transmission. *No energy Ecovillage* portrays off-grid settlements with radical net reductions that eliminate all need for market energy. This could reduce carbon by 14% and land by 5%, which corresponds to the baseline impact of household energy. This scenario simulates pre-industrial lifestyles with respect to energy while keeping other consumption constant. The proponents of this vision mentioned zero energy constructions (e.g., bio-constructions, solar heaters, biogas digester, etc.) in order to maintain decent living standards (SI data)[76].

Supplying *Water off-Grid* through natural sources offers slight impact reduction. This is due to the large role of government subsidy in water infrastructure and supply. Even if eliminating centralized water supply might be unrealistic today, recent studies signal the feasibility of replacing engineered grey infrastructure by natural infrastructures to enhance water capture, availability and quality[77]

Discussion

The construction of scenarios is one of the most important tasks in sustainability[14,78,79]. While most resource-assessment scenarios deal with hypothetical trajectories of techno-economic development[80,81], few explore the potential of demand-side solutions[14,16,30] and even fewer embed the views of non-academic stakeholders[46,47]. Paradoxically, the most encouraging sustainability scenarios rely heavily on citizens adopting sustainable lifestyles[14,79,81]. Hence, identifying and supporting lifestyles changes that are environmentally sound, socially accepted and politically feasible is key for current mitigation and adaptation challenges[29,81].

In this study, we built scenarios based on stakeholders' visions of sustainability to distinguish the options with most potential from those that are seemingly fruitless or present backfire risks. By simulating scenarios in an economy-wide model, we identified that the most sustainable sufficiency scenarios (net consumption reductions) are curtailing motorized transport, reduce market services via the shared economy, conserve energy, reduce food waste and more durable fashion . Green consumption (consumption changes) show the most potential in shifting towards plant-based diets, sharing and repairing appliances, retro-fitting insulation for passive housing and switching leisure and entertainment for community-oriented cultural and sports services.

The risk of green

As expected, all sufficiency scenarios are exempt of trade-offs i.e. they show unanimous reductions across footprints. On the other hand, green consumption scenarios shift expenditure towards the goods that stakeholders perceived as more "environmentally-friendly", presumably based on their lower-carbon emissions. In fact, while some green consumption scenarios yield reductions in carbon and toxicity, they show potential risk of increasing land and water. This trade-off typically occurs when replacing carbon-intensive goods with land and water intensive renewable fuels, materials and crops.

Noteworthy that carbon emissions are invariably harmful for climate stabilization[82]. However, the negative health effects of toxicity depends on the concentration and exposure[83], while the effects of land-use and water are highly dependent on how the local forest, cropland and water are managed[84]. If sustainable resource management were a global norm, replacing carbon-intensive goods by water and land intensive alternatives might be a better short-term alternative[84]

Although sufficiency options are generally more efficient and less risky, they are not as popular as green consumption[27,56,85]. Elements of our green consumption scenarios prevail in "green growth" agendas of industrialized and developing countries[86–88] , although their efficacy has been questioned[80,89,90].

Lifestyle changes in the Shared Socioeconomic Pathways

The sufficiency and green consumption scenarios that we model here are compatible with the most desirable scenario of the Shared Socioeconomic Pathways (SSP), the SSP1 "Sustainability – Taking the Green Road" which is most compatible with mitigation and adaptation[80,81]. Its central feature is high environmental awareness and moving towards less resource-intensive lifestyles, starting by high-income countries[80]. However, detailed lifestyles changes are not represented in the SSP research because the demand sectors of Integrated Assessments Models (IAMs) are aggregated into industry, energy and transportation[81]. We foresee research opportunities in liking EE-MRIO with IAM-SSP research by adding heterogeneity and allowing for more stylized scenarios[91,92].

Displaced impacts and intra-generational solidarity

Commitment to allow and help the world's poor meet their needs is argued by some as an attitudinal pre-requisite for sustainable lifestyles in wealthy countries[93]. At least half of food and clothing impacts embodied in European consumption have consequences abroad (black bars on Figure 2). Changes in European diets and fashion would relieve land and water resources in producing countries, which are typically more vulnerable[94]. However, reducing meat and clothing also benefits Europeans by reducing domestic carbon and toxicity due to less processing, packaging and shipping. Sustainable housing mainly benefits European impacts due to territorial electricity generation and local sourcing of fuels. Appliances and electronics are largely produced outside Europe and thus reducing manufactured products yields more benefits in foreign lands. International cooperation for sustainability could prioritize the lifestyle changes that yield most bi-lateral benefits. Europe could solidarize with the Global South through subsidies and knowledge transfer that encourage sustainable resource management in the producing countries[84,95].

Democratizing sustainability narratives

Scientists might have the duty to connect the pieces of the sustainability puzzle by applying a systems perspective to identify opportunities and risks. However, everyone has the right and responsibility to decide their lifestyles and to steer society towards the common good. Steering can be done by bottom-up initiatives, benevolent governments, mass civil disobedience or by pressuring the powerful to take action[38]. In any case, steering efforts are ideally informed by scientific evidence in order to be most fruitful. For science to be relevant to citizens, the results should speak to their demands. For this to happen organically, citizens and scientists would ideally co-create knowledge[46,96].

Participatory modelling integrates citizens into sustainability research and agendas[46]. Its purpose is to engage implicit and explicit knowledge of stakeholders to create formalized and shared representations of reality. Most systems sciences accommodate this principle, e.g., agent based modelling, system dynamics, network analysis, futurism and knowledge engineering. However, participatory research is not commonly coupled to Industrial Ecology tools nor to EE-MRIOs. We expect that the growing transparency and data accessibility in these fields will encourage further similar efforts[97,98].*[GV1]*

Involving citizens in public decision-making enhances empowerment and intrinsic motivation[99], which are prerequisites for long-term and self-driven lifestyle changes[100]. Further, citizen consultation can point to individual[66,101] or social[102] co-benefits in quality of life that come with sustainable lifestyles, which may serve as policy leverage and speak to citizens' needs.

Co-benefits and barriers of sustainable lifestyles

Sufficiency measures could hinder economic growth and employment under the current work-growth paradigm[53]. To prevent negative social effects, labor and welfare institutions would require different practices to decouple wellbeing from paid employment. Examples of new welfare practices include work-sharing or basic income schemes[40,53]. Indeed, many of the backcasting visions went beyond environmental concerns to include wellbeing aspects, such as working less, social connections, being healthier or having more free time[42,48]. Such aspects go beyond our modelling scope but could be interesting leverage points for policymaking. To complement the environmental analysis, we conducted a literature review of the individual and societal co-benefits and challenges associated with the modelled scenarios, summarized in table 5.

Sustainable lifestyles might have potential co-benefits beyond environmental reductions. Current European diets are characterized by an intake of animal products above dietary recommendations for saturated fat and red meat[47]. Substitution of high saturated-fat, high-calorie meats, and processed foods with fibre rich foods, fruits and vegetables has been linked to reduced risk of coronary heart disease[50]. Individuals with frequent walking or cycling habits show better mental and physical health than their sedentary counterparts[51]. Lower environmental pollution from renewable energy has proven benefits for public health[52]. Relying less on market services and more on shared economy correlates with social empowerment and sense of community[53].

Encouraging sustainable behaviors by offering economic rewards might be counter-productive for people's motivation as it diminishes the satisfaction in altruistic acts[54,55]. Instead, stressing the non-economic benefits of sustainable lifestyles such as quality of life, social justice or animal welfare could engage communities and provide the leverage to overcome the challenges mentioned in table 5[54].

Table 5 Literature review of individual and societal well-being as well as potential challenges implied in the lifestyles changes.

Policy intervention	Individual wellbeing (psychological and health)	Societal wellbeing	Potential challenges
Diet change: reduced consumption of animal products (Food) *Mediterranean, Vegetarian, Vegan*	• Health benefits, e.g. lowering meat, saturated fat and process food reduces risk of heart disease, diabetes and obesity[66,101]. • Compassion and connectedness with other living beings[103] • Affordable adequate nutrition [67]	• Ecosystems services enhanced by resource conservation, e.g. water, land use [66,101,104–107] • Biodiversity and habitat conservation through reduced deforestation[108]. • Increased food security[101] by less food competition of human and livestock. 40% of cereals are animal feed.[101]Reducing overconsumption of resource intensive food might increase affordability of healthy diets for vulnerable groups[101,109]. • Animal welfare and human right to nutrition[110]. • Reduced antibiotic resistance from livestock production can lead to increased public health [108]	Knowledge to ensure adequate nutrition of macro and micro-nutrients through a vegan diet[107].
Food Sufficiency: reduce food consumption and waste *Eating less, Less waste*	• Health benefits of eating recommended energy intake [6,67] • Financial savings [102,105]	• Resource conservation and ecosystems health [105,111] • Solidarity[112] and food security for the poor[6,102] • Reduced obesity and other public health issues related to food surplus and overconsumption [111] • Social inter-connectedness, e.g. through sharing and donation campaigns [113] • Resource-efficient and waste-conscious culture [114].	• Malnutrition[108] • Increased food knowledge on cooking and storage[114].
Food Supply: reduce environmental intensity of production *Local/Seasonal, Organic*	• Reduced immune and respiratory illness linked to agro-chemicals[108]. • Higher energy and micro nutrients per mass[72,115].	• Food environmental sustainability as soil productivity is conserved for the long term [108,115] • Reduced risk of plant pathogens spread through monocultures[108]. • Resilience: Food autonomy and crop diversity [116] • Reduced logistics e.g. transport, packaging [69,117]	• Reduced yield for some crops[72] • Unclear regulations and labelling[72] • Land availability conflicts [115] • Reduced food variety and security [115] • Increased food knowledge to adapt to seasonal and local availability [114,115]
Mobility: reduce motorized transport *Bike and Walk, Less Transport, Work from Home, No flying, Less Cars*	• Physically engaged commute lowers risk of obesity, depression and cardiovascular diseases [108,118–122] • Financial savings[123] • Well-being, e.g. more available time for leisure and work-life balance[124122] • Improved air quality in cities	• Social inclusion by ubiquitous and accessible commute[118,125,126]. • Reduce technological lock-ins that are resource intensive such as car and roads [108,122,127]. • Conservation of biodiversity and cultural heritage by less infrastructure [128] • Urban settings that prioritize public spaces and walkability[122,129,130] are associated with quality of life and safety[131] • Reduction of health and social burden associated with motorized transport, e.g. respiratory and cardiovascular diseases, traffic deaths and toxic emissions [108,122,132]	• Ensure capabilities for transportation, e.g. street lighting, footpaths and cycle lanes [108] • Flexible work might blur life-work boundaries [133] • Quality and coverage of public transport [122] • New attitudes towards public transport[108,134]
Shelter : reduce and shift of energy demand *Renewable Electricity, Ecovillages, Passive House, nZEB*	• Reduced respiratory diseases from particulate matter[108,135], • Efficient buildings reduce dampness and mould, airborne infectious disease, heat and cold exposure [101,121] • Well-being, e.g. connection with nature, strong community and family ties, increased comfort [132,136,137]	• Public health benefits from renewable energy associated to decrease in disability-adjusted life years [101,120,138] • Regional sustainability and increased energy access are positively related with living standards[126,139,140] • Reduced energy poverty [132] • Increased awareness and empowerment to climate action by self-managing energy sources [126]	• Ecosystem and social costs associated with renewables, e.g. biodiversity loss, noise generation, impact on local systems [132,141]. • Political willingness to encourage new technologies and skills [126]
Construction: reduction and shift (Construction)	• Natural materials reduce risk of hazardous exposure [108]	• Preservation of culturally significant places, e.g. historic buildings[132]	• Risk of housing deficit [108] • Natural materials might be scarce and require more maintenance[108]
Clothing: reduction and shift *Durable Fashion, Natural Fibres, Local clothing*	• Financial savings[142] • Natural and plant fibres can offer comfort, breathability and durability[143] • Building an identity based on being more and having less[144].	Lower impact to ecosystems and human health and resources conservation [145,146], decreased air emissions from transportation [143] Promote conservation values and culture e.g. extending the clothing lifetime [142]	• "Guilt-free" fashion might lead to a rationalization of consumption. and throw-away culture[147]
Reduce manufactured products and services *Less chemicals and plastics, Offline Minimalist, Durable appliances, Share & Repair, Local services, Community services*	• Well-being through reduced time and dependency in devices and social media [137]. • Non-market services can enable stronger community bonds [137,148]	Environmental benefits, e.g. prevent marine pollution [141], resource conservation and elimination of surplus production [16,126,149], low environmental intensity of services relative to other goods[8]. Social benefits, e.g. reduction of deaths and illnesses caused by hazardous chemicals [108], less social burden of diseases [148]. Economic benefits, e.g. empowerment and self-governance [149]. Build human capital through learned skills[150] Strengthening of the community, e.g. resilient and self-sustaining communities [149], collective use of resources, resisting technological obsolescence [16,129], build local competence and knowledge exchange[132].	• Emissions offset, e.g. impact of transportation associated with renting [129]; social unrest by displacing market services or overall increased consumption [147] • An aggressive shift form market to non-market services might lead to unsatisfactory services and diminish quality of life[33].

Strengths and Limitations

Modelling consumption scenarios through an EE-MRIO enables a global perspective and multi-criteria analysis. Although we focus on Europe, we expect the general direction of our results to be applicable to other continents, with differences in the magnitudes and share of foreign impacts.

One challenge of coupling qualitative assessments from backcasting to an MRIO framework is that some environmentally relevant lifestyles lie beyond the scope of Input-Output modelling. For example, non-technical visions that encourage co-habitation (persons per dwelling) and downsizing of houses (area per person) might have significant potentials, but require a different assessment[6,65,151]. In general, top-down scenario modeling could be more precise when coupled to bottom-up physical data such as urban infrastructure, transport fleet or household characteristics[9]. To address this, we introduced physical data and constrains for energy and food to enhance the realism of the model.

EE-MRIO is of linear nature and thus disregards second order effects such as cost savings, price responses or economies of scale[52]. In reality, we expect that scaling up alternative consumption patterns would have non-linear effects due to social tipping points and learning curves[31]. The advantage of the linear and snapshot nature of the method is that it allows for testing multiple simulations in isolation, which makes it straightforward to interpret without so many “black-box” interactions.

Reducing or changing consumption can lead to savings, which consumers may spend on other impactful goods, thus triggering a rebound effect[152]. In the SI, we repeat the analysis considering the potential income rebound effect by modelling savings as increased consumption, according to current expenditure patterns[52]. We report the rebound effect as a sensitivity measure but acknowledge that voluntary lifestyle changes driven by environmental values might not be subject to rebound[34,153,154].

Conclusion

The sustainability transformation requires not only innovative technologies but also innovative lifestyles and engaged, well informed, citizens. In this study, we connect backcasting visions to EE-MRIO to systematically assess scenarios of sustainable lifestyles and provide a scoreboard of the options across consumption domains[48,155]. We confirm that some lifestyle changes envisioned by European citizens are promising options, with the additional perk that citizens demand such changes and that they are compatible with increased quality of life.

Except for switching to plant-based diets, the lifestyles with most potential generally imply curbing consumption towards sufficiency levels. While we contrast sufficiency and green consumption to show the independent contribution of each scenario, some scenarios are not mutually exclusive and may be implemented synergistically to yield greater benefits. By studying multiple environmental indicators we detect fewer trade-off risks and larger impact reduction synergies for sufficiency lifestyles, compared to green consumerism. Because European lifestyles drive significant impact abroad, it is key to take responsibility by cooperating with trading partners to deploy sustainable resource management, fair-trade and greener supply chains.

This study provides an overview of the options for change and their consequences for the purpose of comparison. Hence, our results are indicative of potential but not policy conclusive. In practice, the outcome of the scenarios would largely depend on the implementation pathways. We rather present a framework to integrate citizens' perspectives and imaginative alternatives into sustainability scenarios to broaden the range of demand-side solutions.

Participatory modelling for sustainability can be seen as building human capital via social learning or knowledge co-production[156]. Its practice enriches scientific research, the participants and, if taken to its ultimate consequences, the general public, by leading to policies that truly consider the visions and needs of citizens. Understanding the global consequences of local visions and actions is a pre-requisite to focus efforts on the promising options, and stir governments, industries and communities towards them.

Supplementary Information

The Supplementary Information includes methodological details and data to model food and energy scenarios through a physical layer. We discuss the relevant assumptions regarding the adoption rates of scenarios. We present an uncertainty analysis assuming an income-rebound for the scenarios that yield savings. We conduct a literature review on the co-benefits and challenges for quality of life associated to the scenarios as well as their scalability assumptions. The supplementary data file includes all the results on the environmental assessments for each scenario. We include the full inventory of literal text extracts from the backcasting workshops that were used to build scenarios, including the consumption implications and modelling decisions.

Acknowledgements

This work is part of the GLAMURS project financed by the European Union's seventh framework program (contract 613420). We thank all the researchers in GLAMURS who organized, held and documented the backcasting workshops and those who contributed directly to the text coding of reports for this paper: V. Pandur, C. Polzin, M. Petri, I. Thronicker, M. Curuk, H. Martínez, A. Díaz, A. Panno, F. Maricchiolo, A. Brizi, I. Oman, P. Lahner, and E. Leising. We thank Kam Sripada for her assistance proofreading this manuscript.

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PAPER III

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

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Scientists and policy makers recognize the need to address consumption and lifestyles in order to reconcile environmental and development agendas[1,2]. Sustainability-oriented grassroots initiatives emerge bottom-up to create opportunities for sustainable lifestyles[3–5]; yet no prior assessment has ascertained the efficacy of their members to reduce carbon emissions. We compare the carbon footprint (CF) of non-members and members of grassroots initiatives in the domains of food, clothing, housing and transport. We further compare the groups by testing the influence of socio-economic variables that are typically associated with both footprint[6–8] and well-being[9,10]. Here we show that grassroots initiative members have 43% and 86% lower carbon footprints for food and clothing respectively compared to their regional socio-demographic counterparts. We find greater active travel distance and lower indoor temperatures for initiative members, yet no significant differences in the CF of housing and transport. Interestingly, increases in income are not associated with increases in the total CF of members, while the influence of income is confirmed for the CF of the total sample. Instead, factors such as age, household size, and gender better explain the variation in the domain-specific CFs of initiative members. Finally, members show higher life satisfaction compared to non-members and are 11-13% more likely to evaluate their life positively. Our results suggest that initiative members uncover lifestyle features that not only enable lower emissions, but also decouple emissions from income and well-being.

With the United Nation's 12th Sustainable Development Goal of Sustainable Production and Consumption, the global community aims to reconcile economic development and environmental protection[2]. While technical progress may increase the resource efficiency of production it can also lead to undesirable rebound effects[11]. Hence, technical progress in itself is not sufficient to reduce emissions, and behavioral policy interventions or voluntary lifestyle changes are needed to reap the full benefits of cleaner production[1].

Given that household consumption drives about 65% of global carbon emissions[12], there is a major interest in embedding demand-side solutions into climate change mitigation strategies[1,11]. Examples of consumer-oriented policies include creating economic[11] and non-economic[13,14] incentives, social norm-based interventions[15], behavioral 'nudges' by making low-impact choices the default option[1,4], and locking-in desirable behaviors through adequate infrastructures[4,16]. However, consumer-side policy interventions have their own pitfalls. They can be costly and short-lived if they do not hit the deepest leverage points of social transformation[17–19]: the underpinning values, goals, intrinsic motivations[13] and world views that govern society[15,18].

Even individuals with pro-environmental orientations may be ineffective at reducing their CF due to the dominant influence of socio-economic factors on consumption levels[8,20]. Particularly, they may focus on behaviors that are easy to adopt, but have relatively small impact[20,21] e.g., recycling. Further, the available voluntary lifestyle changes are often limited to consumption of less harmful goods i.e. "green consumption"[4,22], and constrained by institutional, infrastructural and behavioral lock-ins[16,23]. For these and other reasons, pro-environmental knowledge[5,21], attitudes[5,20] and even behaviors[24] are no guarantee of substantial impact reductions[20,21,24].

Membership in environmental organizations has been reported to influence the intention-behavior gap[19,25,26]. As a variable, membership captures the relevant social context in which individuals develop or re-inforce environmental attitudes, habits and lifestyles[26]. However, few studies assess the environmental impact of members and they do so through behavioral proxies[8,20,27] or direct energy use[25], overlooking the behavior-impact gap[28,29]. Previous research has been limited to study active and passive members of broadly defined environmental organizations, ranging from multi-national non-governmental organizations to charities[8,21,26,27].

Sustainability-oriented grassroots initiatives are bottom-up networks of individuals and organizations with an overarching agenda of social and environmental well-being[4,9]. They are fueled by voluntary contributions of labor and resources and function through social learning by developing new practices and skills[5]. The sustainability causes sought by grassroots initiatives vary widely. Initiatives can be specialized such as food and energy cooperatives, or comprehensive, such as the Transition Town Movements[30] and eco-villages[5]. Some initiatives focus on satisfying needs beyond market offer by taking a role of "prosumers" and producing the goods they wish to consume[4,5]. Other try to modify or extract themselves from current structural hurdles[5]. Overall, all initiatives attempt to create alternative social practices that best align with the values and envisioned lifestyles pursued by their members[4,27,31].

Grassroots initiatives can influence society on multiple levels[5]. At the individual level, initiatives offer knowledge, role-models and social support to adopt sustainable lifestyles while satisfying needs[4,32]. At the group or network level, they enrich social capital by spurring social learning[5,33], mobilizing for environmental citizenship[22] and incubating innovation niches[23,33]. At the societal level, they can influence the underlying rules and norms, creating a supportive normative context for sustainable policies[15,18]. When successful, grassroots initiatives operate at the deepest leverage points[17], challenge current paradigms[18], and empower individual and collective political agency[18] towards sustainability transformation[3].

Indeed, previous research indicates that grassroots initiatives play a role in sustainability transitions[4,5,18,22,30,33] by providing counter-narratives of economic development with an embedded perspective of intrinsic motivations, values underpinning social relations and pathways to sustainable lifestyles[34,35]. In this sense, grassroots initiatives have a role in fostering voluntary simplicity. Contrary to the notion that consumption determines well-being[9,10], proponents of lifestyles driven by voluntary simplicity argue for a "double dividend": simultaneously reducing consumption while enhancing well-being[9,10,31]. Previous studies suggest that participation in grassroots initiatives could be linked to increased awareness and environmental behaviors, while supporting individuals in the pursuit of well-being and quality of social life[27,31,34].

In this study, we test for evidence of voluntary simplicity by exploring the carbon footprint and well-being of members of grassroots initiatives. We advance from behavioral proxies and direct energy use by estimating the carbon footprint embodied in the most impactful consumption domains[6,12], covering both direct energy use and indirect impacts through purchase of goods and services. Noteworthy, we do not test for causality between joining an initiative and environmental or well-being outcomes. Rather, we test for observable carbon and life satisfaction differences between members and non-members, while controlling for relevant socio-demographic factors.

Here we analyzed the CF of 141 members of 12 sustainability-focused grassroots initiatives located in Italy, Germany, Romania and Spain. The studied initiatives include food and clothing cooperatives, eco-villages and the Transition Town Movement. Seven of the sampled initiatives engage with the production, distribution or consumption of food as one of their main activities (see Methods). We evaluated the individual CF and life satisfaction of initiative members and compared them to non-members sampled from the same geographical regions (N=1,476).

We based our analysis on a self-reported survey which captured demographic variables, socio-economic status, expenditure, environmentally relevant behaviors, living standards, and life satisfaction. We calculated the embodied CF of food, clothing, housing and transport from expenditure, travel and dietary surveys, and housing conditions. We controlled for socio-economic and demographic variables to compare groups through a multiple regression analysis. Finally, we used evaluations of life satisfaction to assess well-being across groups and in relation to CF. The methods and Supplementary Information (SI) contain further detail about the samples, survey items and CF calculations (SI1-3).

On average, initiative members have 17% lower average CF relative to non-members, with 7.8 versus 9.3 tCO_2eq/cap. Results from an independent one-sided *t*-test suggest that initiative members have significantly lower total CF (t=2.34, P=0.010). Across quartiles, initiative members have 7% (Q1), 11% (median) and 20% (Q3) lower total CF (Fig 1).

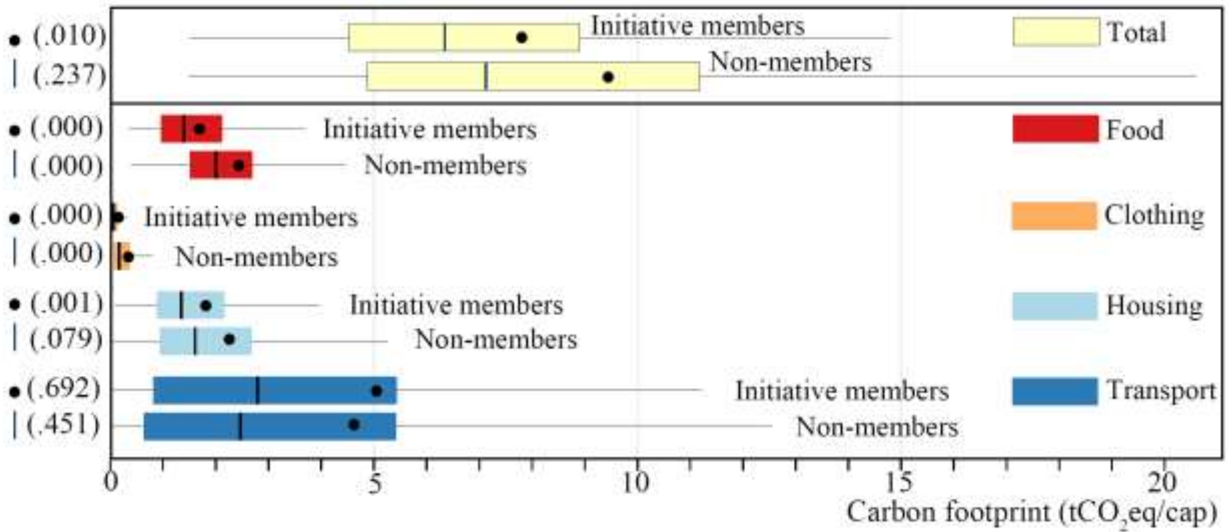

Figure 1| Distribution of annual carbon footprint by consumption domain (in tCO_2eq/capita) of initiative members and non-members. Dots • represent mean values and lines | represent medians. Boxes describe the 25th percentile (left hinge), and 75th percentile (right hinge). Whiskers describe the minimum and maximum values in the absence of outliers (±1.5 x Interquartile range). Outside values are excluded. P values (on the left) indicate the significance of mean (one-sided two-sample *t*-test) and median (equality of medians nonparametric test) CF differences between initiative members and non-members regions. See the SI4-5 for more detailed data overview and statistical tests.

By consumption domain, initiative members have lower food and clothing CF across quartiles (Fig 1). The average food CF for members is 1.6 tCO_2eq/cap, compared to 2.4 tCO_2eq/cap for the non-members (t=5.50, P=0.000). For clothing, the average CF is 0.1 and 0.3 tCO_2eq/cap for initiative members and non-members, respectively (t=13.13, P=0.000). Similarly, the results indicate that the medians of the two samples are statistically different at conventional levels. We do not find a similar pattern for housing and transport. The members' average CF is 1.8 and 5.0 tCO_2eq/cap for housing and transport, respectively (compared to 2.2 and 4.6 tCO_2eq/cap for non-members). Although the *t*-test points to significant differences in housing CF between the samples, the result is likely influenced by inter-group differences in socio-demographics, such as income and urbanization as discussed below.

We perform multiple regression analyses to compare the CF of initiative members with their socio-demographic regional counterparts (Table 1). The estimated models include the natural log transformed values of domain-specific footprints as dependent variables. The independent variables are initiative membership (*INITIATIVE*), income (*INCOME*), additional socio-demographic factors, and country-specific fixed effects to control for observed differences across individuals. Thus, the *INITIATIVE* coefficient is interpreted as the percentage change in the domain-specific footprint associated with initiative membership, holding everything else constant. A negative and significant coefficient would be favorable from a climate change mitigation perspective, as it suggests an actual CF reduction. We report 95% Confidence Intervals (CI) in parenthesis. Our model and the choice of additional socio-demographic controls has been motivated by prior literature, particularly income level, education, gender, family status, age, urban typology and household size[6–8,26].

Table 1 | Multiple regression coefficients indicate the influence of socio-economic variables on the log transformed carbon footprint (kgCO_2eq/cap) of initiative members compared to the total sample.

	Total CF		Food CF		Clothing CF		Housing CF		Transport CF	
	Total	**Initiatives**	**Total**	**Initiatives**	**Total**	**Initiatives**	**Total**	**Initiatives**	**Total**	**Initiatives**
INITIATIVE	-0.155**		-0.425***		-0.857***		-0.124*		-0.082	
	(0.07)		(0.05)		(0.13)		(0.07)		(0.16)	
INCOME	0.27***	0.104	0.048***	-0.016	0.225***	0.136	0.045**	-0.074	0.248***	0.282*
	(0.02)	(0.06)	(0.01)	(0.05)	(0.03)	(0.14)	(0.02)	(0.08)	(0.04)	(0.16)
HHSIZE	-0.050***	-0.021	-0.010*	-0.041*	-0.061***	-0.236**	-0.115***	-0.125**	-0.028	0.052
	(0.02)	(0.03)	(0.01)	(0.02)	(0.02)	(0.11)	(0.03)	(0.05)	(0.02)	(0.06)
FEMALE	-0.119***	-0.198	-0.179***	-0.165*	0.026	-0.083	-0.007	-0.097	-0.227***	-0.662**
	(0.03)	(0.13)	(0.02)	(0.09)	(0.06)	(0.25)	(0.04)	(0.11)	(0.08)	(0.31)
AGE	0.039	-0.053	0.064***	0.183**	0.103**	0.380*	0.227***	0.246**	-0.113*	-0.554*
	(0.03)	(0.14)	(0.02)	(0.09)	(0.05)	(0.21)	(0.04)	(0.11)	(0.06)	(0.28)
EDUC	0.057***	-0.078	-0.024***	-0.121	0.077**	-0.132	-0.000	0.157	0.140***	0.028
	(0.01)	(0.12)	(0.01)	(0.08)	(0.03)	(0.15)	(0.02)	(0.11)	(0.04)	(0.21)
RURAL	0.069***	0.050	0.003	-0.051	-0.017	-0.677***	0.089***	-0.210*	0.171***	0.010
	(0.02)	(0.09)	(0.01)	(0.07)	(0.04)	(0.16)	(0.03)	(0.12)	(0.05)	(0.21)
MARRIED	-0.026	0.017	0.099***	0.184*	-0.016	-0.169	-0.157***	0.036	0.049	-0.050
	(0.04)	(0.16)	(0.02)	(0.11)	(0.07)	(0.25)	(0.05)	(0.14)	(0.09)	(0.32)
Country effects	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
AdjustedR^2	0.131	0.046	0.293	0.332	0.183	0.204	0.226	0.157	0.069	0.175
Obs.	1499	92	1569	104	1432	96	1607	132	1446	117

Unstandardized beta coefficients and robust standard errors in parenthesis. Dependent variables in logarithmic form, by consumption domain. Country-specific fixed effects and constant included. Significance level: *p<0.1, **p<0.05, ***p<0.01. See SI for further detail on independent variables and correlation tests. The total sample includes initiative members and non-members.

We find an *INITIATIVE* coefficient of -0.15 (-0.29, -0.02) pointing to a significant (at the 5% level) difference between initiative members and non-members in terms of total CF (Table 1). The effect is stronger for food and clothing, -0.43 (-0.52, -0.33) and -0.86 (-1.11, -0.60), indicating that members have about 43% and 86% lower food and clothing CF. The *INITIATIVE* coefficient is insignificant at the 5% significance level for housing and transport, reflecting similarities between initiative members and non-members in these domains. Our model explains between 7-29% of the variance in the CF across consumption domains for the total sample (Table 1).

Figure 2 confirms inter-group emission differences on a sub-domain level. Although initiative members exhibit a 23% higher CF in vegetables and fruits, this increase is outweighed by a 32% lower CF of meat, 31% lower CF of dairy products, and 33% lower CF of miscellaneous foods (Fig 2). The lower CF of initiative members reflects the combined effect of lower expenditure in food and clothing, and lower carbon intensity of consumption due to dietary differences (less frequent consumption of meat, dairy products and processed food) and a higher share of second-hand clothing (SI5).

Our findings for housing and transport are consistent on a sub-domain level, with insignificant *INITIATIVE* coefficients for CF associated with consumption of electricity, space and water heating, land and air travel (Fig 2). We find no differences between initiative members and their socio-demographic counterparts in terms of dwelling characteristics, living surface, electricity consumption, heating demand and systems, commuting distance, car ownership, and number of long-and short-flights.

Domain-specific differences between initiative members and non-members may be explained by the constraints associated with specific low-carbon behaviors. While decisions around diets and clothing may better reflect individual preferences, mobility and housing choices are often constrained by long-lived infrastructure, urban design, public transport options, and commuting distances[11]. It is worth noting that we find significant behavioral differences even within the more structurally-constrained domains of housing and mobility behaviors, with initiative members tolerating lower home temperatures in the winter (β=-0.9, $p<.01$, unit: preferred room temperature in °C) and commuting more by cycling and walking (β=1786, p=.013, unit: annual km) (SI5).

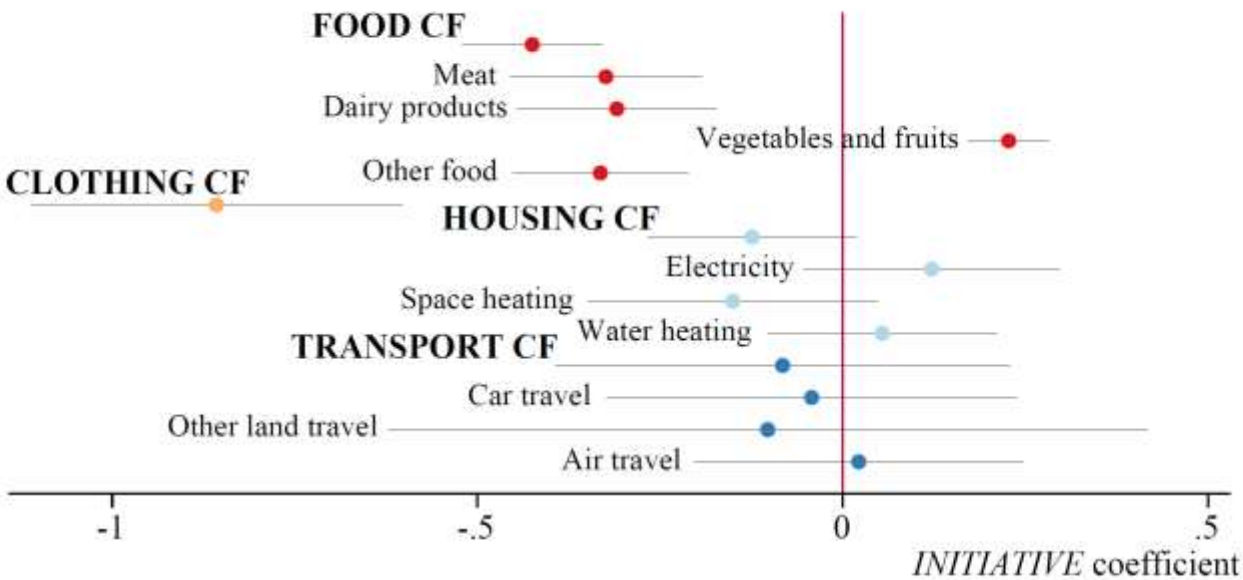

Figure 2: *INITIATIVE* regression coefficients incl. 95% CI. Carbon footprint (CF) by consumption domains and sub-domains. Full regression output included in SI5. When zero is included in the CI, one cannot conclude significant differences in the CF of initiative members. Other food includes processed food, beverages, fish products, and dry legumes.

We confirm income as a significant driver of CF for the total sample[6,11,36]. The shift to a higher income class is associated with a 23% and 25% increase in the CF of typically income-elastic domains such as clothing and mobility[12](Table 1). The same shift is associated with a 5% increase in the CF of food and housing, reflecting the low income elasticity of domains that serve basic needs[12].

Yet changes in income class (*INCOME*) do not explain variation in the CF for initiative members in any of the consumption domains. The *INCOME* effect is no longer significant for initiative members (except the partially significant coefficient for transport). In terms of consumption and behavior, for initiatives, higher income does not imply higher expenditure on food, clothing and electricity, car ownership or increased travel. Instead, we find other socio-demographic variables such as household size[7,36], gender[7], and age[7,36], and country-specific fixed effects[6,36] to explain % of the members' CF variation across consumption domains (Table 1).

Finally, we screened for differences in life satisfaction[37] between samples to test whether reduced CF jeopardizes well-being[9,10].We confirmed that the lower CF for initiative members is not associated with lower life satisfaction; on the contrary, members scored even higher across most items of the life satisfaction scale. We conducted ordinal logistic regressions and displayed marginal effects with regards to the *INITIATIVE* coefficient (Fig 3).

We find highly significant inter-group life satisfaction (LS) differences for three of the five items (LS1-3), and partially significant for LS5. Initiative members are 7-9% less likely to evaluate their life negatively by disagreeing with life satisfaction statements (Fig 3, aggregating effects in red and orange for LS1-3). Members are also 11-13% more likely to evaluate their life positively (Fig 3, aggregating effects in blue for LS1-3). Our findings suggest that lower consumption-based impacts and higher well-being are compatible for members of grassroots initiatives.

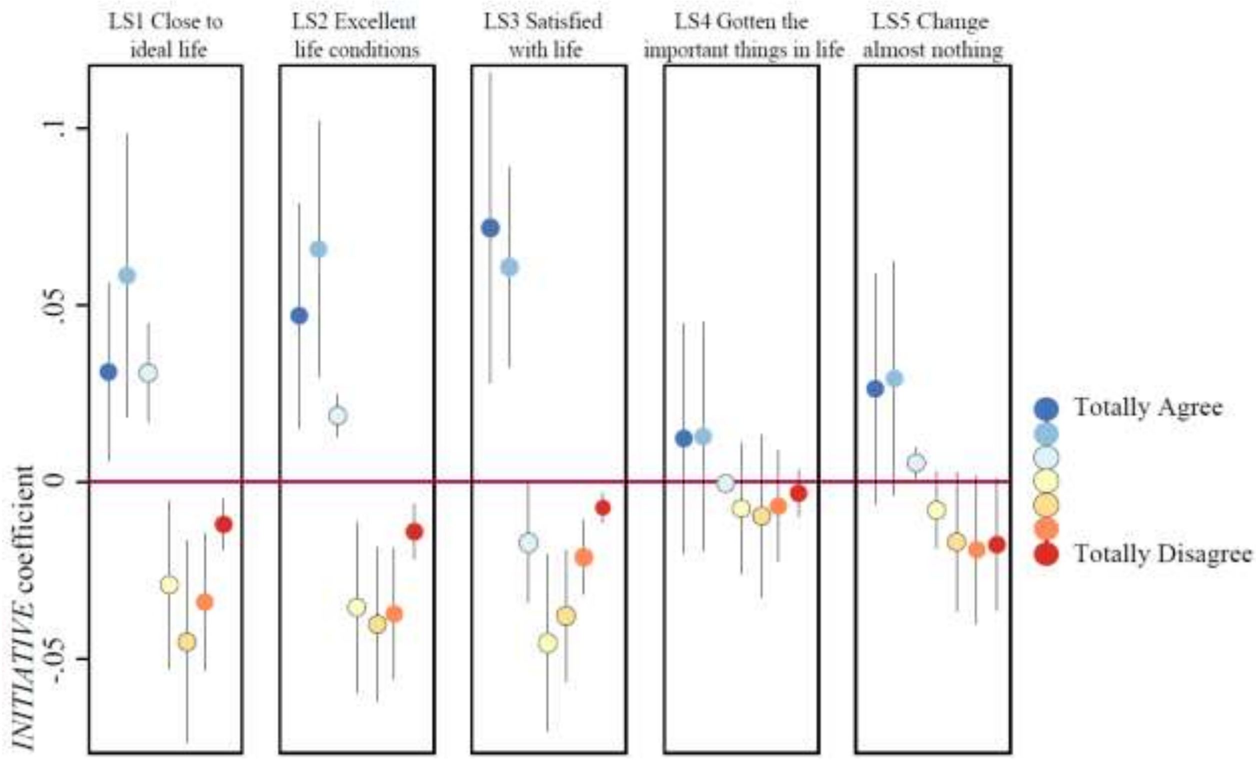

Figure 3: Average marginal effects of *INITIATIVE* effect incl. 95% CIs based on ordinary logistic regression across the five LS items. Each LS item (dependent variable) is measured on a 7-point scale from "Totally disagree" (in red, indicating low life satisfaction) to "Totally agree" (in blue, indicating high life satisfaction). Odds ratios included in SI5.

There are some limitations with regards to the type of initiatives sampled. Our sample includes comprehensive grassroots initiatives such as the Transition Town movement and eco-villages, but lacks initiatives specialized in housing and mobility e.g., co-housing, downsizing, car sharing, cycling[33]. Thus, our results are not conclusive in these domains and further investigation of such initiative niches is needed. Similarly, no sampled initiatives target electronic appliances and devices. Initiatives such as Repair Cafés, where people develop repairing skills and swap appliances, may yield reductions in the CF of manufactured products.

Our assessment is focused on carbon –however other resource savings might be associated with initiative membership. Members consume significantly less food and clothing, which are particularly water and land intensive[12]. Thus, consumer-side shifts in these domains will be relevant even under a low-carbon energy scenario. Even though initiatives membership is associated with lower climate impacts, the observed reductions are insufficient to bring European consumption within planetary boundaries[38]. The average CF of initiative members is still about five times higher than the per capita quota of 1.6 tCO_2eq[38] and further efforts are required to reach the target.

We find members of grassroots initiatives not only to exhibit lower carbon footprints and higher life satisfaction, but also to decouple consumption emissions from income and well-being. For members, lower consumption is compatible with higher well-being, supporting the notion of voluntary simplicity[5,10,31]. Previous research suggests that voluntary simplicity is positively associated with mindfulness[31] and that participating in grassroots initiatives spurs self-awareness of underlying values and behavior[39]. Further, engaging in grassroots initiatives might expose participants to a combination of stimuli such as information, setting goals, public commitments, social norms and behavioral feedbacks, all of which can potentially influence behavior, by creating new habits or reinforcing existing ones[5,8,14,19,25,26,30]. In this sense, social learning and group interaction are not only mechanisms through which knowledge and skills are shared, but they also stimulate the questioning of the current narratives of consumption and well-being, including institutional logics, power relations and the goals of the current systems and lifestyles[5,33,35,40,41].

Large scale diffusion of grassroots initiatives may lead to social tipping points by offering opportunities for low-impact behaviors[14,15] and higher social well-being to a wider audience. Diffusion can happen through upscaling, by attracting more members or embedding initiatives into institutional frameworks[30,42]. While initiatives might benefit from collaborations with official institutions in terms of resources and visibility[43], it might also crowd-out members[44] or weaken key aspects such as governance, accountability, inclusion and autonomy[5,30,33,43]. However, not all initiatives are equal candidates for upscaling[43]. Replication or "out-scaling" is another option for diffusion, it happens when equal or similar initiatives emerge in other geographies[45,46]. Finally, translation of initiatives is the process through which grassroots innovations are translated to other consumption domains[46,47]. Noteworthy, some grassroots initiatives might aim to remain low-scale and local, and thus diffusion might not be a de-facto goal[42]. Rather than focusing solely on upscaling existing initiatives, policies should consider incubating and supporting emerging initiatives to outlive their typical financial challenges by providing visible physical space, facilitate training and provide financial operating resources[5,30,33], as well as support trans-initiative networking efforts[48].

As social innovations, grassroots initiatives might be more efficient than government or markets at satisfying certain social needs: by offering affordable products such as organic food or renewable energy, creating innovative governance arrangements, establishing alternative economic circuits[46] or proto-institutions that embed new sustainable lifestyles[34]. Quantifying multi-level, multi-criteria, and long-term environmental and social effects of initiatives remains an interesting challenge for future research in this area.

In summary, we find grassroots initiatives membership to shed insights towards the goal of sustainable consumption and production (SDG12) by decoupling footprints from income (SDG8) and reconciling environmental conservation (SDG13-15) with enhanced well-being. We consider grassroots initiatives to be worthy of further research and policy consideration as a strategy for the transformation towards sustainability.

Methods

Samples

The sample of non-members (N=1,476) were inhabitants from the regions of Galicia (Spain), Banat-Timis (Romania), Lazio (Italy) and Saxony-Anhalt (Germany). The initiative sample (N=141) included 12 grassroots initiatives with varying sustainability focus. The sample of initiative members in Galicia included 59 members from the food cooperative *Zocamiñoca* (n=40), and *Amarante Setem* (n=13), and *Equus Zebra* (n=6), which focus on food and clothing consumption. The sample from Banat-Timis included 20 members from *Aurora* and *Amonia Brassovia* eco-villages. The sample for Lazio included 27 members of five initiatives, a network of agricultural and food cooperatives with focus on food consumption and regional production of organic food: *CoRAgGio*, *CoBrAgOr, Associazione Parco AgricoloCasal del Marmo, Terra!*, and *daSud*. The initiative sample from Saxony-Anhalt comprise 35 members from *Transition Town Halle* (n=21) and *Lebensmittel retten Magdeburg* (n=14). The former is of an extensive scope while the latter focuses on sustainable food consumption and food waste prevention.

The non-member sample was recruited in a multi-stage process with a phase of contacting participants via a snowball-system (ES, RO and IT) and an external contractor (DE). The initiative members participating in the survey were recruited from the initiatives operating in the regions and the survey was sent to members through electronic mailing lists. See SI1 for further detail about initiative scope and activities.

Survey

We developed a standardized questionnaire to gather self-reported data on environmentally relevant behaviors, consumption, socio-economic and demographic status, life satisfaction and living standards. The survey was first set up in English, followed by translations and adaptations to the official languages of each region. Most items of the questionnaire were kept identical, with regional adaptations being included for socio-demographic variables, in order to respect the contextual conditions of each region.

We ran a pilot study in the regions of Galicia (n=94) and Saxony-Anhalt (n=50) in order to test for clarity, comprehension and validity of items. The final survey was distributed as an online questionnaire between the months of December 2015 and February 2016. Additional detail on the survey can be found in SI2.

Self-reported data may be a subject to bias when respondents align responses with social norms or identity[26,49]. However, we did not expect this bias to influence our results. The carbon footprints at the domain level are not based of single-item measures but rather combine multiple variables (SI3). Additionally, the survey included cross-check items to test for coherence and bias (e.g., annual kilometers registered in the odometer should approximate bottom-up weekly car travel).

We used the Satisfaction with Life scale to measure the cognitive component of subjective well-being. The scale consists of five life satisfaction (LS) items (LS1-5). It was developed to indicate overall subjective life satisfaction beyond objective indicators of material well-being[37]. The following statements were evaluated by respondents with a seven point scale from (1) *Totally Disagree* to (7) *Totally agree*: LS1: In most ways my life is close to ideal, LS2: The conditions of my life are excellent, LS3:I am satisfied with my life, LS4:So far I have gotten the important things I want in life, LS5:If I could live my life over again, I would change almost nothing. Variable scales and definitions are documented in the SI4.

Carbon footprint

We designed a carbon footprint (CF) model to capture most of the carbon emissions, according to prior carbon assessments of household consumption in the European Union[6,12].We quantify the CF of food, clothing, housing and mobility, domains that capture the majority of household environmental impacts in Europe[6,12]. Due to survey length constraints, we did not captured details on the consumption of manufactured products and services, as these categories are composed of a wide range of goods (e.g., education, insurances, computers, white goods, etc.). Omitting manufactured products and services, our assessment encompasses between 65-81% of total household CF across the selected geographical areas[6]. Our calculations were not based on one type of measure, but on considering behavioral, living standards and expenditure variables, as described below and at length in SI3.

We calculated the carbon footprint of food based on dietary habits and weekly frequency of consumption of certain food products. We then approximated daily intake estimates by using the EFSA Comprehensive European Food Consumption database[50], which reports country-specific data on kilograms of food product intake per kilograms of body mass (e.g., meat, dairy products, vegetables and fruits)[50] and normalized with the respondents' weight to approximate food intake by product. We conducted a literature review on lifecycle assessments to calculate product-specific carbon intensities per kilogram of product intake to calculate the individual carbon footprint of food intake per person. We used expenditure on store-bought food to estimate the impacts associated with the food products that were not covered directly in the survey: processed food, fish, beverages and dry legumes. We coupled expenditure on these items with regionalized monetary carbon intensities from EXIOBASE2.3[6,51] (see SI3 for further detail). We enquired about regular clothing spending and applied regionalized monetary carbon intensities[6] while discounting the share of second-hand consumption, and thus assigning impacts only to purchases of new clothing.

Electricity impacts were derived from reported monthly payments in winter and summers, prices per kWh and country-level carbon intensities from Eco-Invent2.2[52]. We used a model for space heating based on climate and building characteristics. We derived the effects from typical energy demand in archetypical buildings in Europe, reported by the TABULA project[53]. Theoretical energy demand (kWh/m^2-annum) was estimated based on the (1) type of house, (2) year of construction, (3) level of insulation and (4) climate zone of the region. Total space heating needs per person were calculated according to dwelling surface and normalized per person according to household size. The hot water demand was calculated in function of occupants for a European household. Carbon emissions of hot water and space heating consider the heating technologies and fuels used by the household[53]. See SI3 for details on housing energy calculations and emission factors.

We based transport footprints on air and land travel. Respondents reported weekly travel patterns, specific transport mode for each trip, number of return trips, approximate distance per trip, purpose of the commute (work vs private trips), and carpooling. Air travel was based on annual number of short- and long-haul flights. We derived lifecycle multipliers per km-passenger from a literature review to apply to transport mode. We calculated specific emission factors per kilometer for private vehicles considering vehicle type, size and fuel (see SI for further detail). We calculated annual CF per capita in 2015 in carbon equivalents (see SI3). The magnitude and shares of calculated emissions across consumption domains align with previous top-down regional assessments[6]. We reported all data exclusions, measures, footprint validations, and input data for the footprint model in the SI3.

Analysis

We used descriptive statistics, parametric and non-parametric tests of central tendencies, and multiple regression modelling to compare differences between initiative members and control regions in terms of individual CF. We examined the distribution of CF by consumption domains across initiative members and non-members, and across geographical areas (see SI4). We particularly examined the means and 95% Confidence Intervals and tested the CF difference using a set of one-sided two-sample t-tests. In addition, we performed Wilcoxon rank-sum test and a non-parametric test on the equality of the medians to address concerns about differences in sample sizes (see SI4), and propensity score matching analysis (see SI5).

We further examined the *INITIATIVE* effect when controlling for socio-demographics and country fixed effects (ES, RO, IT). We performed OLS multiple regression analyses[6,12] using Stata 14 on a domain (Table 1) and sub-domain level (SI5). See SI4 and SI5 for variable definitions and model specification. We included logarithm transformed footprint values as dependent variables to reduce data heteroskedasticity (log-linear regressions)[12,20]. The analysis was performed on annual per capita footprints. We examined main assumptions behind the regression analysis, analyzed pairwise correlations and multicollinearity, and measured practical and statistical significance of the INITIATIVE effect using multiple smile plots by geographical area (see SI5). The specified model is as follows, where CF estimates vary by consumption domain:

$$\begin{aligned} ln(\widehat{CF_i}) &= \beta_0+\beta_1(INITIATIVE_i)+\beta_2(INCOME_i)+\beta_3(HHSIZE_i)+\beta_4(FEMALE_i)+\beta_5(AGE_i)+\beta_6(EDUC_i)+\beta_7(RURAL_i) \\ &\quad +\beta_8(MARRIED_i)+\beta_{11}(ES_i)+\beta_{12}(RO_i)+\beta_{13}(IT_i)+\epsilon_i \end{aligned}$$

Finally, we conducted ordinal logistic (logit) regressions using each life satisfaction items as the dependent variable to examine the effect of initiative membership on well-being (see SI5 for assumptions, odds ratios and average marginal effects of initiative membership).

Uncertainty and validation

We explored footprint distributions and regression results, particularly *INITIATIVE* and *INCOME* coefficients, across the four regions and confirmed that the patterns discussed in the main text generally hold across regions (see SI5). Further, the observed trend of the *INITIATIVE* effect on CF holds true for consumption and behavioral variables (see SI5). We conducted several uncertainty checks to test the assumptions behind our footprint calculations, e.g. flight distance (SI 3.6). Our survey-based CF values for individuals are within the range reported by prior CF per capita assessments of regional household consumption[6]. Domain-level footprint calculations were validated against domain-specific CF of EU regions (see SI3). In addition, we test robustness of our main statistical results (see SI5).

Author contributions

GV and DI contributed equally to the analysis and design of the letter. RGM, AD, EH, and GC contributed to the planning of the research project. DI, GV, RGM, AD, GC, KK and KS contributed to the pilot and final survey design. RGM, AD, KK and GC participated in the sampling, contacted initiatives, distributed, collected and processed the survey data. EH, RW, KS, DI and GV contributed to the carbon calculator model. All authors contributed to the results discussion and manuscript editing. DI and GV share first authorship given their contributions as indicated above.

Competing interests

The authors declare no competing financial interests.

Acknowledgements

This work is an output of the GLAMURS project financed by the European Union’s seventh framework program (contract 613420). We thank all GLAMURS partners who contributed to the survey – in its design, distribution, collection of results and analysis. The list includes but is not necessarily limited to, Alberto Díaz-Ayude and Helena Martínez Cabrera from UDC, Ines Omann, Mirijam Mock, Paul Lauer and Ines Thronicker from UFZ, Fridanna Maricchiolo, Angelo Panno, Ambra Brizi and Eugenio de Gregorio from the Roma Tre University, Irina Macsinga and Vlad Pandur from UVT, Maxie Schulte, Ellen Matthies and Anke Blöbaum from OvGU. The authors thank Angela McLean for writing assistance and Xiangping Hu for his statistical guidance. We would also like to thank Karen O’Brien for providing feedback on an early draft.

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PAPER IV

Household energy footprints and the structural role of durable goods: A study of global developments from 1995 to 2011.

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Abstract

Sustainable Production and Consumption agendas push for high quality, long-lasting goods. Durable goods, however, often require substantial amounts of energy in the form of direct energy inputs and complementary goods and services. As energy demand reduction is one prominent avenue for climate change mitigation efforts, an understanding of the relationship between development and different types of household demand growth is particularly relevant for developing climate policy to target consumer behavior. As such, this work investigates the relationship between energy requirements and the consumption of durable and other goods and services in a temporal and global, cross-country setting.

We calculate the energy footprints (EFs) of 200 goods across the 44 largest economies and five world regions for the period of 1995-2011. We find 68% of the global household final energy is associated directly or indirectly with durable goods, with 51% of the total footprint from fuels and electricity to operate durables, 10% due to the production of durables, and 8% due to consumables servicing durables. The marginal effect of rising income yields 20 to 300% higher increases in durable-related EFs for emerging economies than for advanced economies.

A minimum amount household durables are essential to rise towards decent living standards but a larger bill of goods might lock-in energy-intensive and wasteful lifestyles. Policies and resource use scenarios could benefit from explicitly addressing the resource inertia driven by durables and related goods.

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Introduction

Energy use is fundamental for the well-being of individuals and the development of nations (Pachauri and Rao, 2013; Rao and Pachauri, 2017). Energy access itself might be a prerequisite, however not a guarantee, of improved living standards (Rao and Pachauri, 2017). Reaping the social benefits of energy relies in part on durable goods, such as equipment and infrastructure (Rao and Min, 2017). At the same time, wasteful lifestyles and social practices might foster energy consumption beyond observable social benefits (Mazur, Rosa and Germany, 1974; Steinberger and Roberts, 2010).

While some durable goods are crucial to alleviating energy poverty, increasing expenditure in durable goods invariably raises energy demands directly and indirectly (Ürge-Vorsatz *et al.*, 2012). For instance, using a vehicle requires fuel and other services such as repairs, gasoline dispatch, insurances all of which contribute to the energy footprint of households. Further, some durable goods encourage resource intensive lifestyles and practices. For example, owning a vehicle is associated with carbon intensive transport work and leisure travel (CO_2/km), and with longer commuting distances (Ivanova *et al.*, 2018; Ürge-Vorsatz *et al.*, 2018).

There is an inherent relationship between material stocks such as infrastructure and machinery, and the physical flows and immaterial services needed to build, maintain and operate such stocks (Waldman, 2003; Krausmann *et al.*, 2017, 2018). Household durables can be seen as stocks that foster long-term path-dependencies due to their physical longevity and the social practices that they accommodate (Prata, 2012; Shove and Walker, 2014).

The acquisition of durables has many linked energy requirements, which have not been examined together. Which portion of the global energy throughput is associated directly and indirectly with durable goods? What is their structural role in shaping the future energy needs of the global South? In this study we show, for the first time, an economy wide longitudinal analysis to clarify the direct and indirect contribution of household durables to global energy needs, as well as the different trajectories for advanced and emerging nations.

Our hypothesis is that durable goods have an under-appreciated role in shaping overall energy needs, due not only to increasing operational energy requirements, but also due to the energy embodied in complementary consumables and services that they demand. **Table 1** presents the relevant categories of consumer goods and definitions used throughout this article.

Table 1 | Categorization of final energy consumption by different types of goods featured in this article. Operational energy refers only to the energy content of fuels. The rest of categories refer to energy embodied in upstream production.

▭ **Categorization of final energy by categories** ▭ **Focus of this research**

Durable goods (hard goods)	Final energy in goods that are not purchased frequently e.g., appliances, gadgets, electronic devices, furniture, tools, vehicles, etc. Their useful lifetimes are typically more than 1 year (Oguchi *et al.*, 2017; Krausmann *et al.*, 2018).
Consumable goods (soft goods)	Final energy in goods that are replaced or purchased regularly because they wear out or are used shortly after being acquired e.g., groceries, office supplies, household chemicals, fuels, etc. (Krausmann *et al.*, 2018).
Services	Final energy in immaterial services e.g., public transport, repairs, insurance, health care, spectacles, etc. They may be consumed inside or outside the house.
Operational Energy	Energy content in electricity and fuels purchased and used directly by households to run vehicles, appliances, heat and cook (Ürge-Vorsatz *et al.*, 2012).
Consumables complementary to durables	Final energy in consumables whose consumption is tied to the use of durables. Some examples are engine additives, fuels, lubricants, spare parts, etc.
Services complementary to durables	Final energy in services whose provision is destined for durables. Repairs, maintenance, technical support, IT services, goods insurance, etc.

The environmental impact of household durables

Operational energy is used directly by households by burning fuels for cooking, heating, transport, or running electrical appliances. Indirect or embodied energy refers to all the energy inputs required for the production of goods and services. This includes energy for manufacturing but also the energy required throughout the global supply chains to extract raw materials, produce components, and provide industrial services, transport, and retail. Globally, household consumption is responsible for 65% of the global carbon footprint however, only 20% of those emissions are related to household fuels (excluding electricity), most emissions are embodied in consumer products and services (Ivanova *et al.*, 2016).

The production of manufactured products have been apportioned 16% of the total household carbon footprint (Ivanova *et al.*, 2016). In high-income nations, emissions of household appliances and machinery range from 0.25-0.75 tCO_2e/cap, while furniture and other commodities such as sport goods and toys, range from 1.0-2.4 tCO_2e/cap. Transport-related equipment and audiovisual equipment induce around 1 and 0.4 tCO_2e/cap-yr, respectively (Ürge-Vorsatz *et al.*, 2012; Ivanova *et al.*, 2017).

Durable goods appear to have a modest contribution to global greenhouse gas emissions(Ivanova *et al.*, 2017). Mainly because they are not purchased frequently and, due to their high prices, do not appear particularly carbon intensive per unit of expenditure (CO_2e/EUR). However, durables are rather carbon intensive per unit of weight, ranging from 5 to 21 kg CO_2e/kg of product (Girod, van Vuuren and Hertwich, 2014). Beyond carbon, small and large electronic devices are resource intensive due to their mining and metallurgic inputs (Teubler *et al.*, 2018; Zheng *et al.*, 2018).

Further, durables typically cause most impact during their use-phase due to the complementary resources required to function and idle (Ürge-Vorsatz *et al.*, 2012; Girod, van Vuuren and

Hertwich, 2014). For example, standby energy of large appliances[1] used 236 TWh in 2005, equal to 15% of the total global electricity demand required by large appliances (Ürge-Vorsatz *et al.*, 2012). For appliances such as smart phones and set-top boxes, standby power can be as high as operating power (Grubler *et al.*, 2018).

Energy and lifestyles: well-being-driven lock-in?

Increases in energy footprints are strongly driven by increases in income, which has meant that most countries are not decoupling economic growth from energy consumption (Lan *et al.*, 2016; Wood *et al.*, 2018). Further, higher living standards influence the proportion of direct:indirect energy required by households. Early research showed that a typical poor household exerts circa 65% of its energy requirements through direct energy; for an affluent household, this fraction drops to 35% (Herendeens *et al.*, 1976).

Higher income households in both emerging and advanced economies tend to own more durable goods (Wiedenhofer *et al.*, 2016; Rao and Ummel, 2017; Teubler *et al.*, 2018). By 2050, the number of electronic devices is expected to increase by 80% in the global North, to 42 devices per capita. In the global South, a 3 fold rise is expected to 24 devices per capita (Grubler *et al.*, 2018).

This research adds to previous literature by reporting households' final energy footprints embodied in goods according to their functionality and durability (Table 1). Here we split energy demand into durables and non-durables as a step towards elucidation the links between human needs, consumer choices and lifestyle lock-ins (Prata, 2012). Fostering a transition towards environmentally-sustainable resource use requires a more comprehensive understanding of the stock-flow inertia within households; this research enhances such an understanding.

[1] Refrigeration, fan, washing machine, television and oven

Data and Methods

This study traces the evolution of final energy footprints embodied in global household consumption during the period 1995-2011. We focus on households' durable goods and the complementary consumables, services, and operational energy that they require.

Classification of goods and services

Durable goods such as appliances, furniture, tools, and vehicles are typically not purchased frequently, for they all have a life-span of several years. Consumable goods (e.g., groceries, household chemicals and fuels), on the other hand, are purchased regularly because they wear out or are used up shortly after being acquired (Hausman, 1979; Krausmann *et al.*, 2018). Services such as public transport, repairs, insurance, health care or entertainment are intangible goods that may be consumed inside or outside the house. In this study, we feature as independent categories the consumables and services that complement durables by enabling their operation, maintenance, and repairs.

We classified the 200 economic goods and services in EXIOBASE3 according to their expected lifetime and function (Figure 1). Durable goods typically last more than one year, while non-durables last less than one year (Oguchi *et al.*, 2017). To gain information on the nature and function of goods in our model, we refer to the descriptions by the International Standard Industrial Classification of All Economic Activities (ISIC) (United Nations, 2002). In EXIOBASE3, 28 goods are services, 136 are consumable goods, while 36 are durables, as shown in Figure 1. Further, we identified those services and consumables which depend on the existence of durables. We find 73 "consumables to durables" and only 8 services associated with durables. Operational energy can be used to power transport devices, electric appliances or gas appliances. Our inventory includes 73 energy carriers, of which 10 are transport fuels, 11 are electricity generated from different sources, and 53 are bio- and fossil fuels for heating and cooking purposes. This linking is straightforward for most energy carriers, however a few are ambivalent and could be used for transport or heating interchangeably, such as LPG gas. A further challenge is that we cannot describe the end uses of the fuels e.g., the heating and cooking done with electric appliances. The full inventory of goods and energy carriers, including their classification, rationale, and assumptions is available in the Supplementary Data (SD).

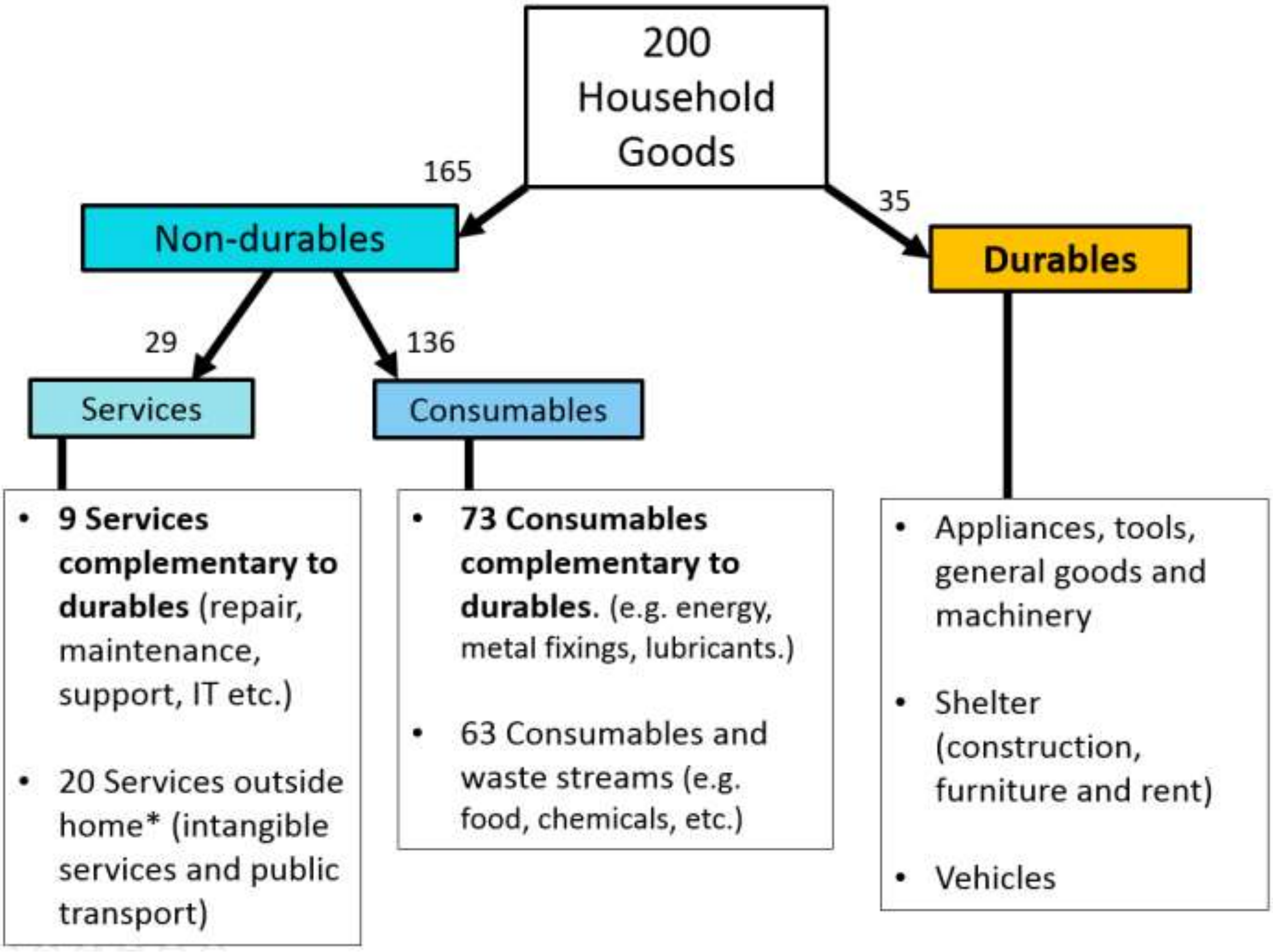


Figure 1 | Classification of economic goods into product categories. Key: 36 out of 200 goods are durables. Representative goods of this category include appliances and tools, housing, furniture, and vehicles. The established categories are exhaustive and mutually exclusive. The Supplementary Data file provides the classification rationale, and a sensitivity analysis to test the effect of our classification decisions. *Residence boundary.

Final Energy Footprint and EXIOBASE-MRIO

We employ consumption-based accounting (CBA) to calculate Energy Footprints (EFs). Unique to this study, we utilise final energy accounts, rather than primary energy supply (see below). Consumption-based accounting (CBA) attributes all production-based emissions and resources to the final goods produced in the economy (Davis and Caldeira, 2010). In this sense, the impact induced directly by final consumers (e.g., households, governments, etc.) plus the embodied impact from all economic goods, including imports, and excluding exports. Here we only consider households' final demand thereby omitting other final consumers such as governments or capital formation (Wood *et al.*, 2018). We use the standard Leontief model to calculate final energy footprints of households as follows(Miller and Blair, 2009):

$$\boldsymbol{FP} = \mathbf{s}\,(\mathbf{I} - \mathbf{A})^{-1}\,\mathbf{y}_h + \boldsymbol{F}_{hh} \qquad (1)$$

Where **I** is the identity matrix, and **A** is the technical coefficient matrix, representing the inter-industry requirements. $(\mathbf{I}\text{-}\mathbf{A})^{-1}$ denotes the so-called Leontief Inverse, the matrix of total requirements. The coefficient vector, $\boldsymbol{s}$, results by dividing the final energy carriers or products used in a given industrial sector by its economic output (i.e. TJ/M EUR). The $\boldsymbol{F}_{hh}$ scalar represents direct operational energy used by households' electricity, transport, heating, and cooking fuels. Finally, the footprint $\boldsymbol{FP}$ represents the total environmental impact induced by a given final household demand $\mathbf{y}_h$ of all goods consumed by a nation.

The footprint calculations in this paper are based on EXIOBASE, an environmentally extended multiregional input-output database (EE-MRIO)(Wood *et al.*, 2014). EXIOBASE3 includes accounts of the economic activity and trade for the world from 1995 to 2011(Stadler *et al.*, 2018). It includes 200 economic goods and services and 163 industrial sectors for each country.

For this paper, we have generated a satellite account of final energy. This refers only to the end use of final energy products, thus discounting exported energy products, energy for own use of energy sectors and energy losses during extraction, transformation, storage and distribution (IEA, 2017). The energy use accounts constructed in this paper are based on the approach described in the supplementary material of Stadler et al. (Stadler *et al.*, 2018). Thus, the extended energy balances of the International Energy Agency (IEA, 2017) are first converted from the territory to the residence principle (see (Usubiaga and Acosta-Fernández, 2015), for more details). From the resulting dataset we calculate the product- and flow-specific final energy use – following the definition above – and allocate energy consumption to EXIOBASE3 industries and products using the same allocation approach as in (Stadler *et al.*, 2018). More details are provided elsewhere (Behrens and Usubia, no date).

We only look at household consumption (hence exclude consumption by government, not-for--profit serving households, and capital formation). It should be noted that the household accounts include all consumed goods including durables, but excludes purchases of residential housing capital stock (European Commission *et al.*, 2008). Consumption of housing services, construction work, real estate, and imputed rent are included in household consumption (Eurostat-OECD, 2012). In our study, we cover the 44 largest economies, which encompass about 91% of global GDP and 65% of the world population. The rest of the countries are aggregated into 5 "Rest of the World" regions representing the remaining countries in the Middle East, Latin America, Europe, Asia-Pacific, and Africa (Stadler, Steen-Olsen and Wood, 2014).

Results

Household energy footprints of durables, services and consumables

Of the total global energy footprint (218 Exajoules EJ), 49% is energy embodied in production of goods and services while 51% (112 EJ) is operational energy. Figure 1 shows the global final energy footprints of households distributed across types of goods. Of the 112 EJ of operational energy, 36% is transport fuels, 14% is electricity, and 50% is household fuels for heating and cooking (see SD for country-specific distributions).

On a global average, total household budget is spent as follows: 12% goes to durables, 6% in consumables to durables, 21% are services to durables, 26% is spent in consumables and 35% is destined to consume services outside home (see SD for details). Household demand drives only 60% of the total global EF (363 EJ for 2011). The remaining 40% is EF embodied in the consumption of governments, non-profit serving households, and capital formation.

Only 21 EJ are embodied directly in durables consumed by households. Specifically, durables use 20% of embodied energy (middle), equivalent to 10% of total EF (right). However, 7 and 8 EJ are durable-related consumables and services, respectively 4 and 3% of the total EF (Figure 1, right). Considering that operational energy, and complementary consumables and services would not have a function without durables, we conclude that the durable-related energy footprint amounts to 148 EJ i.e. 68% of the global energy household footprint in 2011 (**Figure 2** colored in orange).

The total global EF is apportioned by economic groups as follows: 32% is associated with consumption in advanced economies, 44% by emerging and transition economies, and 23% by Rest of the World regions from all continents (see Methods and SD) (Stadler, Steen-Olsen and Wood, 2014).

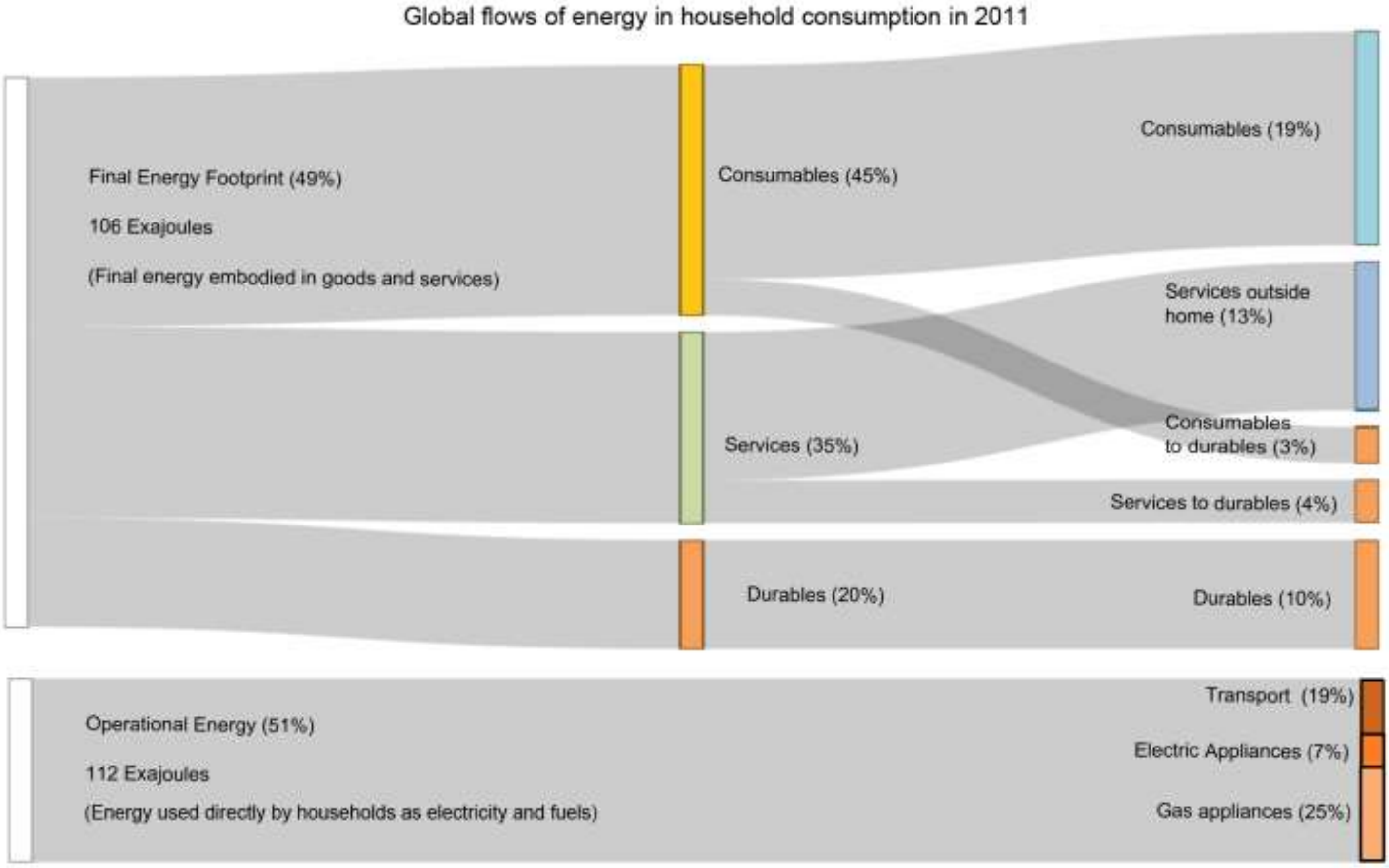


Figure 2 | Global energy footprint of household goods and services. Key: Under the common classification (middle), durables use 20% of global energy embodied in consumption goods. 7% of total final energy is embodied in goods and services complementary to durables (right). Operational energy is required to run durable goods, amounting to 51% of the total final energy. In sum, 68% of global direct and indirect energy is traceable to durable goods for the base year 2011 (in orange). Net energy for households amounted to 313 EJ in 2011, meaning that 95 EJ were either used by the energy sector for non-transformation purposes, or lost in transformation, gas distribution, electricity transmission, and coal transport within the sector.

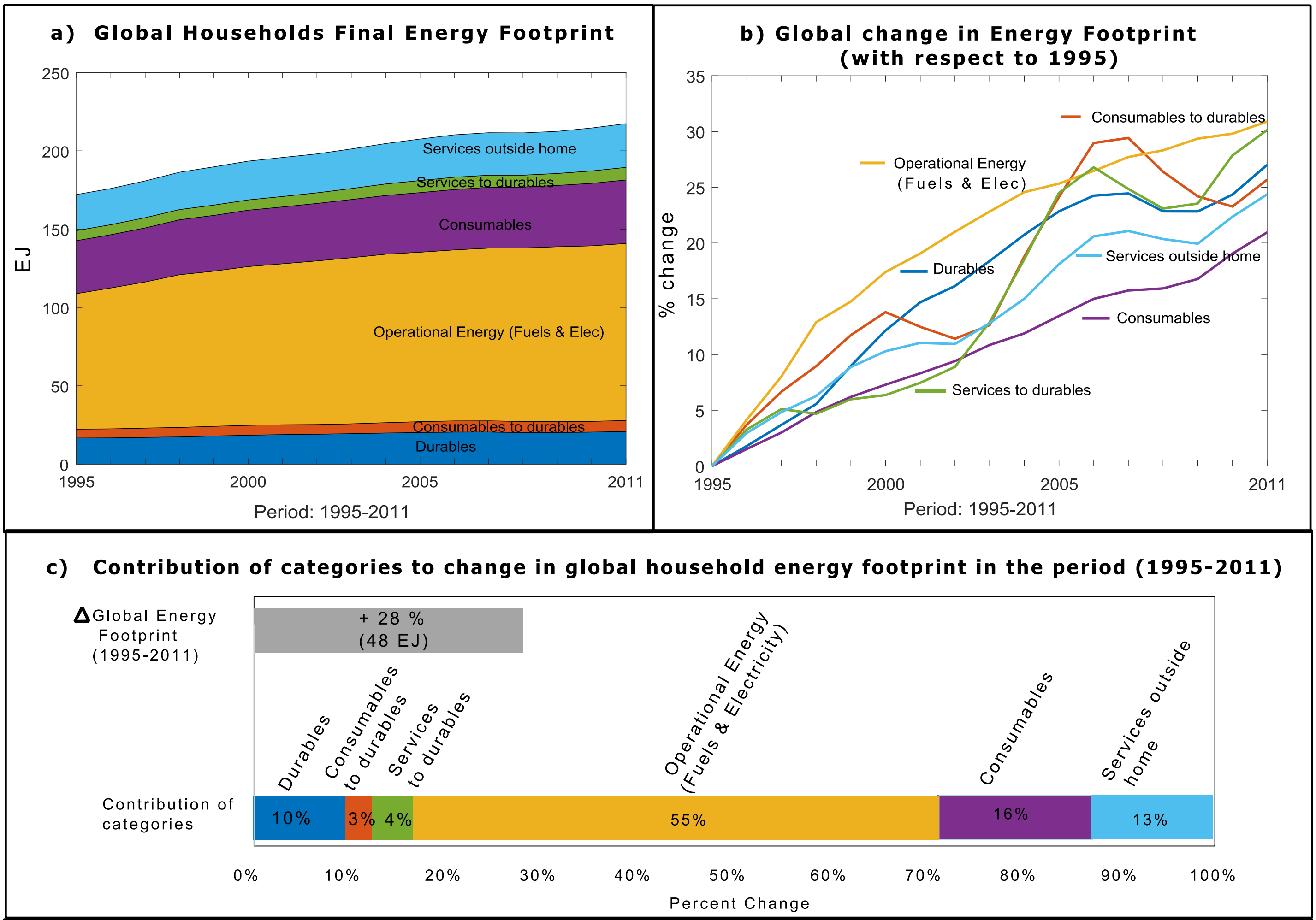
Evolution of energy footprints from households in the period 1995-2011

Figure 3a and b show the evolution of households' EF from 1995 to 2011. Both the absolute changes and growth trends signal the dominance of durable-related energy during the period. The total global EF increased by 28%, equivalent to 48 EJ, of which 4.5 EJ were added by durables, which coincidentally also grew by 28% during the period. Durable-related services, consumables, and operational energy increased by 33, 25 and 30%, respectively, corresponding to 2, 1.3 and 26 EJ. While durables remain below 22 EJ in 2011, 34 of the additional 48 EJ added since 1995 are durable-related. A contribution analysis shows that 72% of the global change was driven by durable-related goods (Figure 3c).

Figure 3d confirms that global trends were strongly influenced by the 34 % growth in EF of emerging economies (18 EJ) and 47% growth in total EF of Rest of the World regions (16 EJ), and to a lesser extent by the 16% growth in advanced economies (14 EJ). In the emerging economies, durables and complementary consumables and services grew more drastically, by 61, 75, and 140%, respectively.

The EF of durables rose steadily since 1995, while complementary consumables and services begun rising more steeply after 2002 (**Figure 3b**). Durables and associated goods follow a similar trend but with a certain lag between them, which can be explained by two mechanisms. First, the inherent functional relationship between durables and their complementary goods (Ürge-Vorsatz *et al.*, 2012; Krausmann *et al.*, 2017, 2018; Teubler *et al.*, 2018). Second, the independent relation of different type of goods to changes in income (e.g., economic recessions) during the period (Wood *et al.*, 2018).

Interestingly, growth in durables and complementary goods was more sensitive to the global economic crisis, manifested as a dip between 2006-2009. In contrast, operational energy and consumables maintained a steady growth during the period, signaling their role as basic goods, which are typically less sensitive to changes in income e.g., food and fuels (Hertwich and Peters, 2009; Ivanova *et al.*, 2016). Below, we discuss the effect income growth for the EFs across country groups (Figure 4 and Table 2).



d) Changes in energy footprints of regions and categories in the period (1995-2011)

	Durables	Consumables to durables	Services to durables	Operational energy	Services outside home	Consumables	Total EF
Advanced Economies	-4%	16%	4%	32%	8%	2%	16%
Emerging economies	61%	75%	140%	16%	76%	41%	34%
Rest of the world	56%	0.4%	58%	48%	45%	45%	47%
Global	28%	25%	33%	30%	27%	23%	28%

Figure 3 |Global evolution of durable-related energy footprints a) Global EFs embodied in different type of goods and operational energy from 1995-2011. b) Global percent change in EFs with respect to base year 1995. Key: the largest changes are detected for all goods related to durables. c) Relative contribution of categories of economic goods to total EF of household consumption, expressed in percentage of contribution. d) Changes in EFs of country groups and categories. Key: the steepest change has been in durables and services to durables in the emerging economies. Key: The global household energy footprint increased from 170 to 219 EJ, of which 72% of the growth was contributed by growth in durables-related EF.

Drivers of energy footprints and consumption

Figure 4 and Table 2 explore the implications of rising living standards on final energy footprints through a correlation analysis across time. Globally, a 10% rise in income corresponds to an 8% increase in the EF per capita (Table 2). For a similar increase in income, the EF of durable goods rises about 9% but complementary consumables and services rise more than proportionally, by 11 and 13%, respectively. Less than proportional changes are observed for inelastic goods such as operational energy (ε=0.68) and consumables (ε=0.8), which are typical values for basic goods (Peters and Hertwich, 2009; Ivanova *et al.*, 2017).

Energy footprints and consumption of durable goods have a stronger relationship to income in "emerging and transition economies", where the consumption of durables rises by 12% in response to a 10% rise in expenditure and the EF rises by 9%. The link is even stronger for the EF of "durable-related" consumables and services, which rises by 16% for this group.

While the durable-related EF coefficients are considerably larger for emerging economies, the consumption coefficients are rather comparable across groups (Table 2). This asymmetric trend can be explained by technology efficiency, manifested as energy intensity (GJ/EUR). Emerging economies are typically more energy intense than advanced economies (Arto *et al.*, 2016).

Table 2 indirectly reflects the dynamics between EF, efficiency and income. The coefficients are much lower for advanced economies, as technological efficiency allows for EF to grow at decreasing rates with respect to income. However, in terms of total footprint, efficiency gains are generally offset by total consumption (Ivanova *et al.*, 2016; Lenzen *et al.*, 2018). We confirm this expectation visually, given that advanced (energy efficient) nations concentrate on the higher end of EF per capita (Figure 4a).

Indeed, despite general decreases in energy intensities (signaled as circles and stars), footprints per capita have mostly increased with respect to 1995 (red square) (Figure 5). The lowest intensities are below 2 MJ/Intl $, e.g., Japan, Norway or Spain. In general, efficiency gains are compatible with reduced per capita EF mostly in advanced economies such as Norway, Belgium, France, etc, however there are two remarkable exceptions from emerging nations: South Africa and Russia. On the contrary, the BRICS and World Regions display abrupt efficiency gains, but their total EF grow moderately during the period (Figure 6). Noteworthy, nations with the highest energy intensities (>3 MJ/Intl $) are composed of an assortment of emerging, advanced, and rest of the world regions e.g., Greece, Taiwan, Canada, Rest of Middle East and Africa, etc.

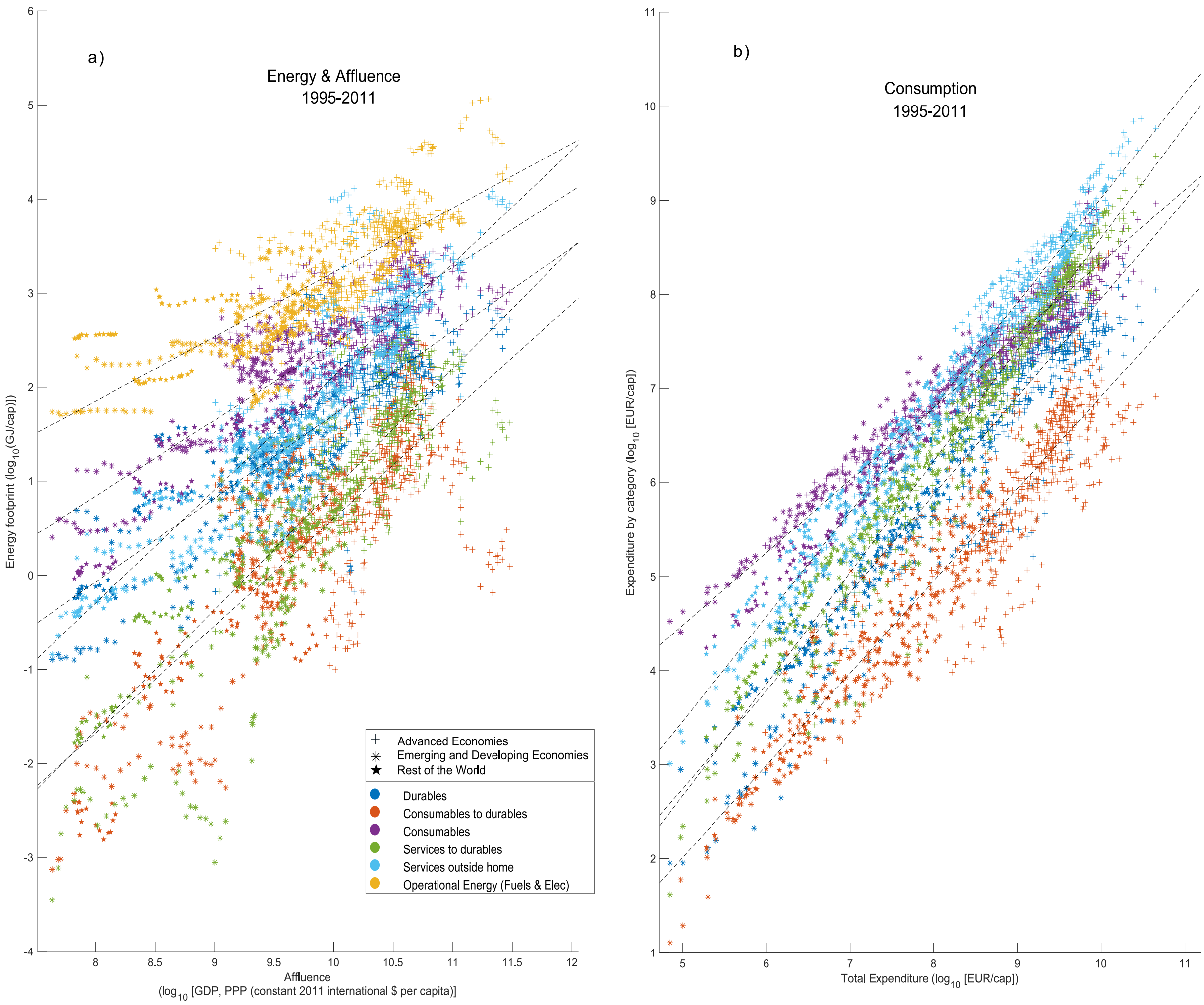


Figure 4 Changes in final energy footprints and consumption of goods. Left, income as driver of the final energy footprint of household consumption categories for different group of nations. Right, consumption of different types of goods plotted against total household expenditure. Country grouping according to the classification of the International Monetary Fund available in the SD (International Monetary Fund, 2018). Key: The dotted lines represent the regression slope listed under "elasticities" in Table 2. Consumption trajectories are more straightforward and nations follow a similar path as income rises through time. Contrary, the EFs show more diverse trajectories across consumer goods, and across and within country groups.

Table 2| Energy footprints and consumption elasticities. Log-log linear regression model for the 1995-2011 time series consisting of 44 nations and 5 Rest of World regions. Left, the log of the households' energy footprints in GJ/cap for each category, region and year (N=833), regressed against income as the log (GDP,PPP const 2011 Intl $/cap). Right, expenditure in each category regressed against total household expenditure (constant EUR per capita). Significance level (p-value): *P < 0.1; **P < 0.05; ***P < 0.01. CI, confidence intervals. 2011 GDP displayed for the country group. Key: The global EF of durables rises 8.9% with respect to 10% increases in GDP, while the demand of durables rises by 10.4% with respect to 10% increases in total global household demand.

Categories	Energy Footprint Elasticity ε (95% CI)		R^2	Consumption elasticity ε (95% CI)		R^2
Global (N=833)		***$ 13,517***	***Intl $/cap***			
Total	0.82***	(0.80,0.84)	0.6			
Durables	0.89***	(0.85, 0.93)	0.70	1.04***	(1.02, 1.07)	0.89
Consumables to durables	1.14***	(1.08, 1.2)	0.64	0.98***	(0.95, 1)	0.86
Services to durables	1.28***	(1.23,1.33)	0.72	1.19***	(1.17, 1.20	0.96
Operational Energy (Fuels and Elec)	0.68***	(0.65, 0.75)	0.67	-	-	-
Consumables	0.81***	(0.78, 0.85)	0.72	0.77***	(0.76, 0.79)	0.94
Services outside home	1.2***	(1.16, 1.24)	0.80	1.12***	(1.10, 1.13)	0.97
Advanced Economies (N=527)		***$ 40,611***	***Intl $/cap***			
Total	0.69***	(0.64.0.74)	0.86			
Durables	0.8***	(0.71, 0.89)	0.36	0.94***	(0.88,0.99)	0.68
Consumables to durables	0.56***	(0.43,0.68)	0.13	0.94***	(0.88,1)	0.64
Services to durables	0.84***	(0.74, 0.93)	0.35	1.25***	(1.22,1.27)	0.95
Operational Energy (Fuels and Elec)	0.75***	(0.68, 0.82)	0.45	-	-	-
Consumables	0.45***	(0.37, 0.51)	0.22	0.71***	(0.68.0.73)	0.83
Services outside home	0.99***	(0.89, 1.08)	0.46	1.18***	(1.15.1.20)	0.93
Emerging and Transition Economies (N=221)		***$ 9,690***	***Intl $/cap***			
Total	0.74***	(0.69,0.79)	0.80			
Durables	0.93***	(0.84, 1.02)	0.64	1.19***	(1.12,1.25)	0.84
Consumables to durables	1.55***	(1.41,1.70)	0.68	0.99***	(0.93,1.04)	0.84
Services to durables	1.54***	(1.36,1.71)	0.57	1.19***	(1.12,1.25)	0.86
Operational Energy (Fuels and Elec)	0.54**	(0.46,0.61)	0.48	-	-	-
Consumables	0.86***	(0.77,0.93)	0.69	0.8***	(0.77.0.81)	0.96
Services outside home	0.93***	(0.84,1)	0.69	1.16***	(1.13,1.18)	0.97
Rest of the World (N=85)		***$ 7,806***	***Intl $/cap***			
Total	0.43***	(0.36.0.50)	0.65			
Durables	0.83***	(0.70, 0.95)	0.69	0.99***	(0.94,1.03)	0.96
Consumables to durables	1.18***	(0.98, 1.37)	0.64	0.99***	(0.92,1.05)	0.91
Services to durables	1.08***	(0.96, 1.19)	0.81	1.08***	(1.05,1.11)	0.98
Operational Energy (Fuels and Elec)	0.13**	(0.03, 0.23)	0.07	-	-	-
Consumables	0.97***	(0.88, 1.06)	0.85	0.89***	(0.85,0.91)	0.98
Services outside home	1.04***	(0.95, 1.12)	0.88	1.08***	(1.04,1.11)	0.98

Final energy footprints across nations

Figure 5 shows the highest final energy footprints for western European and North American nations, with values above 100 GJ/cap. The lowest values, below 30 GJ/cap, are in China, India, Brazil, Indonesia, Africa, Asia, and Latin America. The most energy-hungry populations demand between 4 to 8 times more energy per capita than citizens of the most energy-frugal nations (Figure 5 & Figure 6).

The relative importance of durable goods varies widely across nations, taking on average 10% of the EF (Stdev ± 0.04), while durable-related EF take an average of 63% (Stdev ± 0.09). The patterns are similar for advanced and emerging group of nations, but remarkably different across individual countries. For example, for Great Britain, Taiwan, Malta, Mexico, and the Czech Republic, durable goods constitute between 16 and 20% of final energy footprint. Whereas in Cyprus, Bulgaria, Ireland, and the US, such goods make up less than 6%. The durable-related EF is stacked up until the yellow bar.

In relative terms, the minimum total durable-related energy is 40% (Cyprus) and the maximum is 88%, for Rest of Africa (see SD). The expectation that operational energy would constitute a larger portion of the EF of low-income households is generally confirmed by our analysis (Figure 5) (Herendeens *et al.*, 1976) .

Interestingly, we find a significant strong correlation (slope=0.6096, $R^2 = 0.892$) between the share of durable EF and the ratio of durable EF/durable-related EF. This means that a higher share of durables is associated with a higher durable-related energy footprint. In the SI we exemplify how this relation can be used to estimate the total durable-related EF given a value of durables EF.

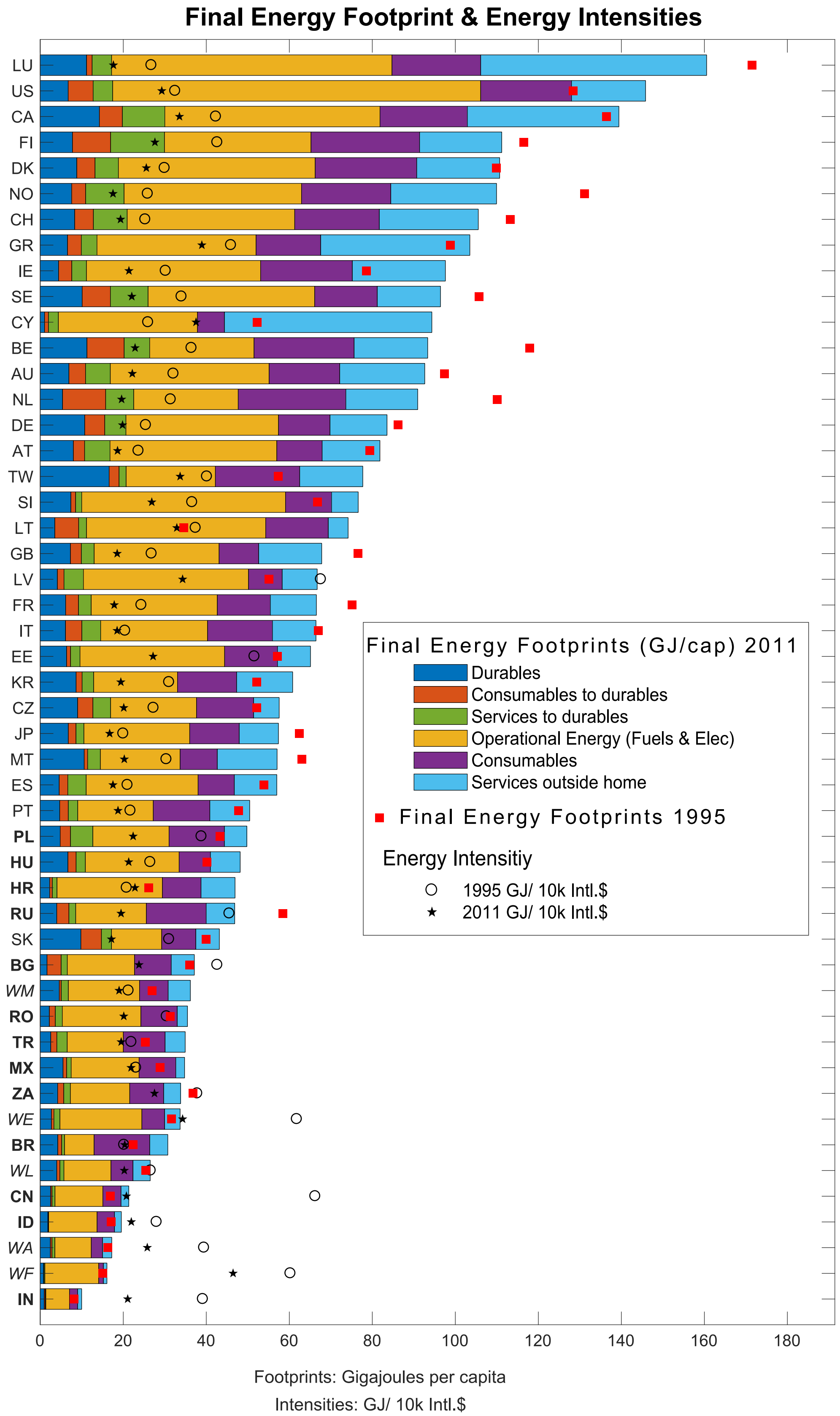


Figure 5 Energy footprints for different goods and energy intensities across-nations. Key: The value stacked up to the yellow bar amounts to durables-related energy. Divide energy intensity (GJ/ 10k Intl. $) by 10 to convert to MJ/intl $. **Bold**:Emerging Economies. *Italics*: Rest of the World regions: WM= Middle East, WL= Americas, WA= Asia and Pacific, WF= Africa.

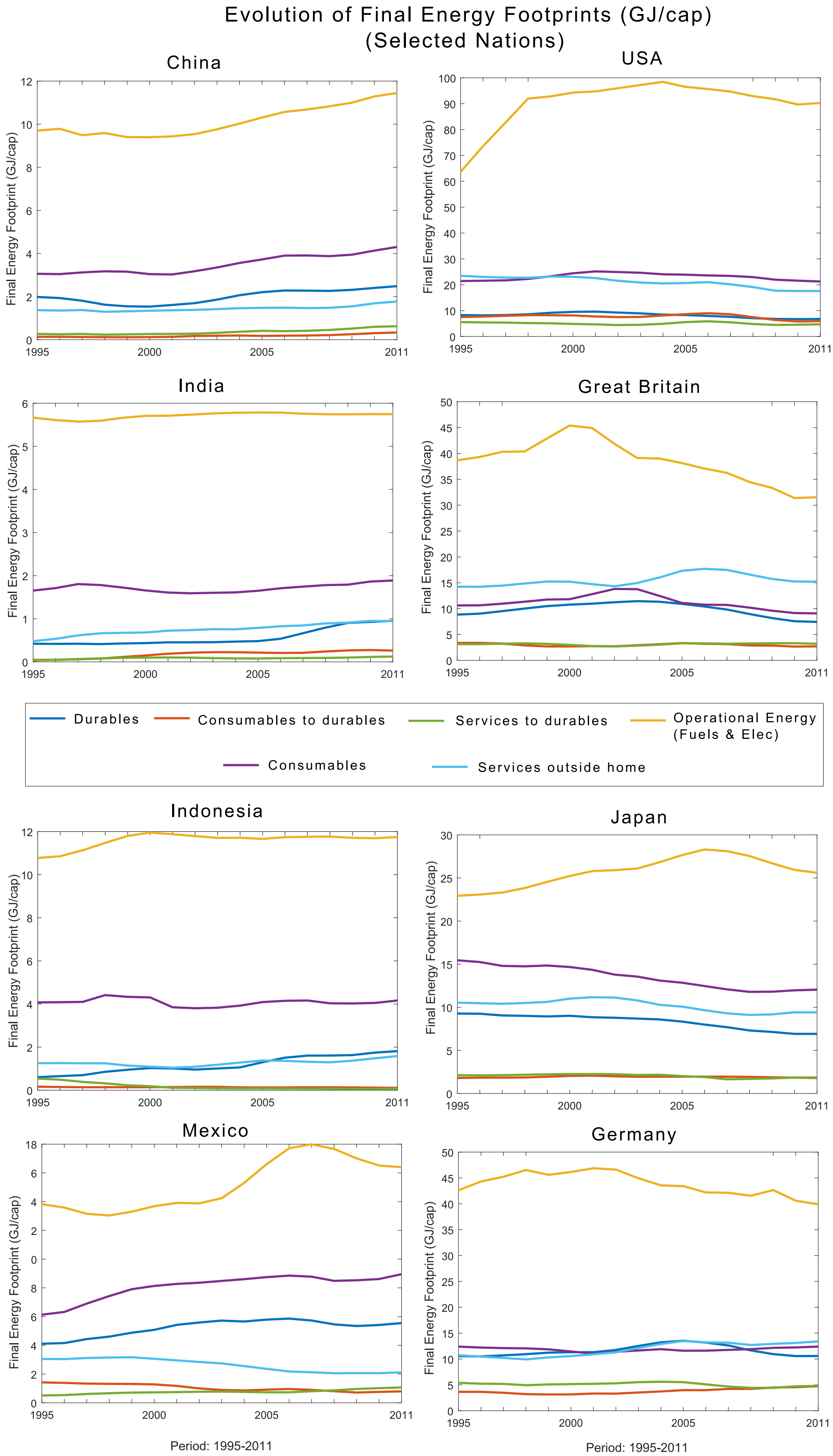


Figure 6 Final Energy Footprints of selected emerging and advanced economies. Key: Durables and operational energy tend to decline after 2005 in advanced economies while complementary services tend to rise (Right). For Emerging economies, durables and operational energy rise during the study period (left).

Top energy-demanding goods

Table 3 shows the most energy-demanding products for each consumption category and country groups for 2011. Transport-related durables and complementary goods emerge consistently as top energy-demanding goods with global EFs ranging 148-648 MJ/cap, but 17-25 times larger footprints in advanced economies than in emerging economies.

The second most demanding group relates to shelter and housing (40-811MJ/cap). This group includes non-energy durables such as furniture and other manufactured products (toys, sport goods, music instruments, etc.) and printed and recorded media. Interestingly, “fabricated metal products” (metal hardware and tools), only show up for emerging economies, possibly reflecting the importance of household work, informal economies, and manual labor (Ironmonger, 2000). Services related to refurbishing, and the provision of housing, are the top demanding services that relate to the built environment.

The third most demanding group is composed of electric appliances and their complementary energy carriers (34-181 MJ/cap). While “communication and media devices” are high for all nation groups, they are 6 times more energy demanding in advanced nations. Interestingly, precision apparatus and computer-related services only show for advanced economies, while electrical machinery and apparatus are only featured in the top durables for emerging economies.

The fourth group is labelled in yellow as “gas stoves and furnaces”, appliances which largely make up the “machinery and equipment” durable group. The embodied energy in producing cooking and heating fuels also features among the highest footprints. Services for repair and retail are shared among several of these durable types due to data aggregation (see limitations). The SD includes the classifications and the detailed description of each product category.

Table 3 | Top energy demanding goods of each consumption categories for different country groups in 2011. The table shows the goods with the highest footprints within each category and country group. The color coding shows the family of durable goods where different goods can be classified. Notice that some consumables and services can be linked to more than one type of durable, due to product aggregation. See the SD for more details on the types of goods that are included and excluded under each EXIOBASE product.

Top energy demanding products for different country groups in 2011										
Categories	**Durables**	**MJ/cap**	**Consumables to durables**	**MJ/cap**	**Services to durables**	**MJ/cap**	**Services outside home**	**MJ/cap**	**Consumables**	**MJ/cap**
Global	Furniture; other manufactured goods n.e.c.	811	Motor Gasoline	477	Real estate services	679	Air transport services	847	Chemicals nec	941
	Motor vehicles, trailers and semi-trailers	648	Gas/Diesel Oil	152	Sale, maintenance, repair of motor vehicles, parts and accessoires	148	Hotel and restaurant services	636	Food products nec	858
	Other non-metallic mineral products	228	Distribution of gaseous fuels through mains	63	Retail trade services*, repair services of personal and household goods	100	Health and social work services	545	Rubber and plastic products	647
	Medical, precision and optical instruments, watches and clocks	181	Distribution and trade of electricity	43	Construction and refurbishment work	49	Other services	217	Vegetables, fruit, nuts	383
	Radio, television and communication equipment and apparatus	178	Products of forestry, logging and related services	40	Private households with employed persons	42	Insurance and pension funding services	202	Wearing apparel; furs	368
	Printed matter and recorded media	174	Electricity by coal	34	Wholesale trade and commission trade services*	41	Recreational, cultural and sporting services	187	Textiles	297
Advanced Economies										
	Motor vehicles, trailers and semi-trailers	2933	Motor Gasoline	2338	Real estate services	2968	Air transport services	3728	Chemicals nec	3563
	Furniture; other manufactured goods n.e.c.	1655	Gas/Diesel Oil	695	Sale, maintenance, repair of motor vehicles, parts and accessoires	728	Health and social work services	2297	Food products nec	3339
	Printed matter and recorded media	822	Distribution of gaseous fuels through mains	263	Retail trade services*, repair services of personal and household goods	393	Hotel and restaurant services	2261	Beverages	1264
	Machinery and equipment n.e.c.	688	Electricity by coal	150	Construction and refurbishment work	142	Recreational, cultural and sporting services	844	Rubber and plastic products	1256
	Radio, television and communication equipment and apparatus	610	Distribution and trade of electricity	148	Private households with employed persons	97	Insurance and pension funding services,	827	Wearing apparel; furs	987
	Medical, precision and optical instruments, watches and clocks	343	Kerosene	146	Computer and related services	74	Other services	762	Paper and paper products	945
Emerging and Transition Economies										
	Furniture; other manufactured goods n.e.c.	423	Motor Gasoline	94	Real estate services	162	Air transport services	229	Chemicals nec	490
	Other non-metallic mineral products	367	Products of forestry, logging and related services	56	Retail trade services*, repair services of personal and household goods	41	Hotel and restaurant services	209	Food products nec	483
	Fabricated metal products, except machinery and equipment	177	Gas/Diesel Oil	45	Private households with employed persons	39	Railway transportation services	147	Vegetables, fruit, nuts	440
	Motor vehicles, trailers and semi-trailers	165	Liquefied Petroleum Gases (LPG)	17	Sale, maintenance, repair of motor vehicles, parts and accessoires	34	Health and social work services	136	Rubber and plastic products	342
	Radio, television and communication equipment and apparatus	102	Distribution and trade of electricity	16	Construction and refurbishment work	28	Other land transportation services	131	Wearing apparel; furs	309
	Electrical machinery and apparatus n.e.c.	97	Distribution of gaseous fuels through mains	15	Wholesale trade and commission trade services*	18	Education services	105	Textiles	235
Rest of the World Regions										
	Furniture; other manufactured goods n.e.c.	1017	Motor Gasoline	174	Real estate services	382	Hotel and restaurant services	520	Rubber and plastic products	837
	Medical, precision and optical instruments, watches and clocks	299	Gas/Diesel Oil	57	Wholesale trade and commission trade services*	73	Air transport services	422	Chemicals nec	376
	Motor vehicles, trailers and semi-trailers	299	Distribution of gaseous fuels through mains	40	Retail trade services*, repair services of personal and household goods	50	Health and social work services	338	Food products nec	241
	Radio, television and communication equipment and apparatus	86	Distribution and trade of electricity	35	Sale, maintenance, repair of motor vehicles, parts and accessoires	45	Other services	132	Vegetables, fruit, nuts	183
	Printed matter and recorded media	57	Electricity by gas	30	Construction work	36	Insurance and pension funding services	111	Wearing apparel; furs	158
	Machinery and equipment n.e.c.	52	Liquefied Petroleum Gases (LPG)	16	Private households with employed persons	22	Recreational, cultural and sporting services	101	Textiles	95

*except of motor vehicles and motorcycles — Stoves and furnaces (yellow) — Electric Appliances (blue) — Housing and non-energy goods (green) — Transport (red)

Discussion

Economic growth and modernization

Durable-related goods individually represent a modest portion of the total EF (~10%), but collectively, and considering operational energy, durables drive two-thirds of household energy needs. Further, durable-related EF have increased steeply since 1995 and is expected to rise closely to income growth in emerging economies.

An income elasticity larger than 1 indicates EF or consumption that changes more than proportional to increases in income. Consumption of durables and complementary consumables and services is sensitive to changes in income ($\varepsilon \geq 1$). Durable-related elasticities are 20% to 3 times higher in emerging economies, in line with the abrupt rise in durable ownership projected for these nations (Grubler *et al.*, 2018) and with the efficiency lag occurring in these nations (Arto *et al.*, 2016). These trends would likely extend into the near future, as income in emerging economies is expected to rise by 5% up unto 16 k Intl $/ cap, by 2030 (International Monetary Fund, 2018).

Altogether, our results clarify the importance of technological efficiency (energy intensity) and economic growth for energy footprints of durables and related goods. However, the diversity of country-specific footprint patterns (Figure 6) suggests that other factors beyond our research scope, such as demographic transitions and political regimes, might play a role (see limitations and discussion in the Supplementary Information).

We find that consumption trajectories are relatively consistent as nations follow a clear path for all categories (Figure 4b). In contrast, the EFs display a wider diversity of trajectories across categories, countries and even within the same country group (Figure 4a). These results signal the interplay between economy-wide energy efficiency and rising consumption for the fate of per capita EFs. In other words, there is opportunity for emerging nations to attenuate the negative effects of economic growth through technological efficiency, yet being cautious of the potential rebound effects that come with cheaper production and household savings (Herring and Sorrell, 2008; Wood *et al.*, 2017).

The role of socio-economic context

happiness. Carlsson et al. (2007), for example, estimate that between 50 and 75 percent of durable goods and real-estate consumption is done for status reasons and between 25 and 50 percent of income is earned for positional purposes. The happiness and respectively – social status gained by positional consumption can then only be maintained by continuous

The functional nature of goods, as well as the socio-economic context, are both tied to income elasticities. Elasticities greater than 1 are typical of conspicuous or "luxury goods". Such goods do not typically achieve satiation and are prioritized with social mobility (Lenzen *et al.*, 2018). On the contrary, basic goods generally display elasticities less than 1, meaning more steady consumption despite changes in income changes (e.g., food, shelter) (Russell and Wilkinson., 1979).

Goods that are relatively cheap, serve basic needs, and are short-lived (such as food and electricity) are consumed relatively steadily despite income changes. Durable goods, on the contrary, normally represent a bigger purchase and do not require constant replacement, therefore leaving room for households to plan their consumption at convenience (affordability, changing needs, bonanza, etc.) (Russell and Wilkinson., 1979). Not surprisingly, the largest coefficients are for the categories with the largest expenditures shares (SD), except for the case of consumables, which are largely comprised of food.

Whether a good is basic or a luxury also depends on socio-economic status. For instance, during economic crises low-income households are the first to curtail consumption or even sacrifice necessities. Durable-related consumption elasticities are near 1 and larger for emerging nations, as durables are still more of a "luxury" there (Rao and Ummel, 2017). On the contrary, above 1 consumption elasticities in advanced economies occur only for "immaterial" services to durables and outside home (travel, leisure) (Hertwich and Peters, 2009; Lenzen *et al.*, 2018).

Larger elasticities for durables consumption in emerging economies aligns with economic theory (Waldman, 2003). The emerging economies are relatively new markets for durables, in response to rising income and living standards (Hausman, 1979; Pachauri and Rao, 2013; Rao and Ummel, 2017). For these nations, the stock of durables is being built and in a growth phase, inside and outside of households (Krausmann *et al.*, 2017; Södersten, Wood and Hertwich, 2018). For advanced nations , the stock of basic durables is arguably in a more steady-state, while personal and smaller devices stock tends to grow (Grubler *et al.*, 2018). Arguably, a large portion of flows are destined to operate, serve, replace, upgrade and incrementally expand the current stock of basic household equipment (Vásquez *et al.*, 2016; Krausmann *et al.*, 2017, 2018) (see discussion in SI).

Stock and flow relationships

Society tends to become more "durable" with modernization. The share of durables went from 28% to 59% (52 Gt/y) of global material throughput in the 20th century (Krausmann *et al.*, 2018), and the current durable stock requires half of total materials to be sustained (Krausmann *et al.*, 2017). Proportions between durables and their complementary flows have been previously established in monetary (Hausman, 1979; Jalava and Pohjola, 2002; Waldman, 2003) or mass units (Krausmann *et al.*, 2018; Teubler *et al.*, 2018).

In this study, we find a relationship for energy flows within the household as well. The "share of durables EF" predicts well the "total durable-related EF", which on average makes up two-thirds of total household EF.

Curiously, we do not find strong correlations when testing one-to-one relationships between durables EF and the EF of related consumables and services (see SD). This could indicate substitutability within durable-related goods e.g., households either buy a gas tank (consumable to durable) or pay for energy services of delivery/supply (services to durables).

Even if the resolution of our model does not allow for specific linkages between goods, physical models report similar patterns (Teubler *et al.*, 2018). This is reasonably intuitive, as durables drive operational energy for appliances, mobility and shelter (Ürge-Vorsatz *et al.*, 2012).

Limitations and Strengths

The main limitations of this paper are inherent to Environmentally-Extended Input-Output analysis, namely aggregation. EXIOBASE is the open access MRIO database with the most sectorial detail currently available. Nonetheless, more product detail is vital for in-depth analysis of the end uses and type of durable goods.

For repair and maintenance services in emerging and low-income nations, the informal (non-market) economy and household production can be a significant source of service provision (Max-neef, Hopenhayn and Elizalde, 1991; Ironmonger, 2000), and this is potentially not described with enough detail in energy and economic statistics. However, for this case, the energy accounts are the main focus, and the advantage of our model is that it accounts for all energy production and use, both formal and informal.

Uncertainty

We found that five economic goods could fit more than one classification, due to their level of aggregation. Our classification choices do not affect the conclusions of this paper, as we show through sensitivity analysis in the Supplementary Information. We also computed all elasticities by testing using income (GDP in PPP) and expenditure (EXIOBASE household demand in constant prices) and found comparable results. We decide to include both variables in the main text, leaving GDP for the EF elasticity to allow for more literature comparison and cross-validation with future research based on other models.

By focusing on households, we overlook the role of political regimes and public investments in providing services and goods that are destined to households. This implies that in some countries household expenditure covers purchases that are covered by governments in welfare states (Stiglitz, Sen and Fitoussi, 2010). This should be considered when comparing household energy across countries. The same applies to capital formation (Södersten, Wood and Hertwich, 2018), as arguably a portion of road and parking infrastructure could be attributed to households vehicles, even if they are built by public or private sectors (Ivanova *et al.*, 2017).

Future work

Finer resolution on durables and linkages to end-uses would provide a richer picture on the observed patterns. Physical information on volume, weight, and units would be crucial to characterize the size and impact of the durable stock, which is expected to follow trends of dematerialization, modularity and miniaturization predicted by Moore's law (see SI of (Grubler *et al.*, 2018)).

A global, disaggregated, time-series database on the consumption of durables that integrates information about physical units, prices (quality), life-cycle production, operational energy efficiency, and lifetimes (designed, perceived, and effective) (Echegaray, 2016; Oguchi *et al.*, 2017) would enable testing and monitoring of policies for sustainable production and consumption (SDG12) and against planned obsolescence.

However, as we show in this research, such a database should not only focus on durables but also jointly assess the complementary services, consumables, and operational energy. This would allow for detecting trade-offs between products and services, as well as rebound effects of leasing, circularity, or shared economy (Intlekofer, Bras and Ferguson, 2010). Arguably, energy footprints are proportional to the bill of durables, regardless of who owns them or supplies complementary services (Intlekofer, Bras and Ferguson, 2010).

In this paper we focus on energy flows the analysis could be repeated by looking at other resources and critical materials embodied in durables in-stock and their end of life impact, which might be significant (Teubler *et al.*, 2018),

Future research could look at the role of non-market grassroots initiatives that promote share and repair practices of durable goods (Akenji, 2014). For example, the Repair Café movement up-scaled from 1 to 1500 cafés world-wide in the past decade, currently repairing about 300,000 appliances per year globally (Charter and Keiller, 2016; Cafe, 2018; Vita *et al.*, 2018).

Finally, consumer data to show the heterogeneity of socio-economic, well-being, and time-use implications of durables would add to this research (Jalas, 2008; Rao and Ummel, 2017). See SI limitations for further discussion on social considerations and existing databases towards improved versions of this work.

Policy Implications: sustainable consumption and poverty alleviation

One of the biggest, most pressing, challenges of our time is to alleviate poverty and ensure universal energy access without jeopardizing natural resources (United Nations, 2016). Progress towards ending poverty (SDG1) measures access to household infrastructures that contribute to raising living standards (United Nations, 2016; Rao and Min, 2017), while progress towards the SDG7 measures access to affordable, reliable, sustainable and modern energy (United Nations, 2016). A focus on energy access without considering the complementary durables is only a partial picture on the resources needed for alleviating economic and energy poverty. (Pachauri and Rao, 2013; Garcia-Ochoa and Graizbord, 2016).

Progress towards sustainable consumption and production (SDG12) is measured by the deployment of the 10-Year Framework of the Programme on Sustainable Consumption and Production Patterns (United Nations, 2016), which calls for increasing lifetimes, reparability, and efficiency of durable goods.

First, it is uncertain whether producing higher quality durables requires more or less embodied energy, as it will depend upon sector-specific technological prospects (Intlekofer, Bras and Ferguson, 2010). Second, even if producing long-lasting and resource-efficient durables reduces their yearly EF, durables alone represent less than 10% of the total EF. Revised policy efforts towards SDG12 would ideally expand into considering the impact of durable-related services and consumables. Moreover, we show that the EF of specific durable types is strongly coupled to income, signaling that efficiency measures alone might be insufficient to substantially curtail energy use (Wood *et al.*, 2017; Vita *et al.*, 2018).

Simultaneously pushing for efficient appliances and longer-lived appliances might be contradictory, as retiring current durable stock to replace with better units implies shorter lifetimes(Oguchi *et al.*, 2017). Further, SDG12 narratives assume durables are short-lived due to poor quality or planned obsolescence, however users' perception, not functionality, often drives shorter lifetimes (see SI discussion) (Echegaray, 2016; Oguchi *et al.*, 2017).

From a stock and lifetimes viewpoint, the observed relationships in this paper might be locked-in in the near future, with the possibility of an increasing role of durables as their ownerships are expected to increase by 80-300% percent for modern lifestyles towards 2050 (see SI) (Grubler *et al.*, 2018)

Concluding remarks

In this paper we analyse the energy footprint (EF) with a focus on the role of durables. Durables directly embody around 16% of total EF across countries. However, when considering operational energy and complementary goods, durables-related consumption drives around two thirds of households' EFs. For emerging economies, we find the steepest growth in durables-related EF and consumption across time and in relation to income.

The most impactful durables-related consumption domains are transport, housing, and appliances, which demand about 10 times more energy per capita in advanced economies than in developing economies. However, for emerging economies, we find the steepest growth in durables-related EF and consumption across time and in relation to income. With the relatively high growth of operational energy in advanced economies, there is clearly a strong need to focus efforts on ensuring that durables purchases, especially in emerging countries, are energy efficient options in order to avoid the energy rise that comes with wealthier economies.

Whilst provide insights into the energy implications associated with alleviating economic and energy poverty, further efforts are needed to link durables to specific human needs. A sobering possibility is that the relationships presented in this paper will extend into the near future, given the life-spans of current household technologies in place, and the infrastructure and lifestyles lock-ins that accompany them. Both policies and resource scenarios could benefit from explicitly addressing the resource inertia driven by durables and related goods.

Supplementary Information and Data

The Supplementary Information includes extended results, discussion, and limitations, as well as a sensitivity analysis. The Supplementary Data contains the concordance matrixes and product description used by our method, as well as footprints, economic data to reproduce our results.

Acknowledgements

This work was conducted during the Young Scientists Summer Program at the International Institute for Applied System Analysis-2017. Supported by the Norwegian Research Council.

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PAPER V

Food Security for an Aging and Heavier Population

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sustainability

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Article

Food Security for an Aging and Heavier Population

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Received: 28 August 2018; Accepted: 8 October 2018; Published: 15 October 2018

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Abstract: Changes in national and global food demand are commonly explained by population growth, dietary shifts, and food waste. Although nutrition sciences demonstrate that biophysical characteristics determine food requirements in individuals, and medical and demographic studies provide evidence for large shifts in height, weight, and age structure worldwide, the aggregated effects for food demand are poorly understood. Here, a type–cohort–time stock model is applied to analyze the combined effect of biophysical and demographic changes in the adult population of 186 countries between 1975–2014. The average global adult in 2014 was 14% heavier, 1.3% taller, 6.2% older, and had a 6.1% higher energy demand than the average adult in 1975. Across countries, individuals' weight gains ranged between 6–33%, and energy needs increased between 0.9–16%. Noteworthy, some of the highest and lowest increases coexist within Africa and Asia, signaling the disparities between the countries of these regions. Globally, food energy increased by 129% during the studied period. Population growth contributed with 116%; weight and height gains accounted for 15%; meanwhile, the aging phenomenon counteracted the rise in energy needs by −2%. This net additional 13% demand corresponded to the needs of 286 million adults. Since the effect of biodemographic changes are cumulative, we can expect the observed inertia to extend into the future. This work shows that considering the evolving individual biophysical characteristics jointly with sociodemographic changes can contribute to more robust global resource and food security assessments. Commonly used static and homogenous caloric demand values per capita might lead to misrepresentations of actual needs. What previous analyses could have estimated as increased food availability, sufficiency, or surplus waste might actually be energy sequestered by the mass of the human lot. Based on the discovered trends, feeding nine billion people in 2050 will require significantly more total calories than feeding the same people today.

Keywords: food security; mixed methods; biodemography; type–cohort–time data; heterogeneous food demand; dynamic population modeling; demographically extended food assessment; short-term human evolution

1. Introduction

Human activity is regarded as the dominant cause of contemporary environmental change, driven by the resources required by populations [1–5]. The most comprehensive assessments on the human–environment relationship traditionally describe resource use as a function of the population's size, affluence, and technology [4,6–12]. Yet, population remains an exogenous variable that is deprived of evolving biophysical traits. Evidence shows that humans changed drastically at the individual and societal levels over the past century. Notably, global life expectancy increased from 36 to 70 years during the 20th century [13]. Similarly, adult height increased as much as 20 cm for some nations in only four generations (100 birth cohorts) [14]. Global average body mass index (BMI) (see Supplementary

Information for a glossary of terms) increased by 0.4 kg/m^2 per decade [15], increasing from 21.7 kg/m^2 in 1975, to 24.2 kg/m^2 in 2014 for male adults [16]. Senescence has been delayed by a decade, leading to a more long-lived species [17]. At the same time, demographic transitions accelerated, driven by an aging population, and decreased fertility and mortality rates [18,19].

Although populations can be seen as stocks of individuals that require constant flows of energy and materials to be sustained, individuals and groups have different and evolving characteristics, which in turn also demand differentiated resources [5]. Beyond population size, what are the implications of heterogeneous and dynamic population characteristics for the sustainability goals? The combined effects of individual biophysical and demographic changes for resources, particularly food, remains poorly understood.

Food security is a global major concern [20]. Ending hunger and granting access and adequate nutrition for everyone is one of the sustainable development goals by 2030 [21]. Yet, research on food availability typically models food production, supply, and losses [22–26]. In other words, most of the assessments on food for human consumption and diets do not actually model "humans", but rather "products".

Indeed, most of the recent assessments on "diets" are based on supply data provided by the Food and Agriculture Organization (FAO) balance sheets and methodologies [12,27]. The common limitation is the scarcity of harmonized bottom–up physical dietary data next to the convenience of food balance sheets maintained by the FAO for most of the countries in the world [28].

> "To compute per capita dietary energy consumption in calories, the FAO has traditionally relied on food balance sheets . . . this choice was due mainly to the lack of suitable surveys conducted regularly." (p. 49, [20])

Moreover, average per capita "food consumption" is commonly calculated as the total food calories supplied in a given country, divided by its total population [12]. Although some authors acknowledge the discrepancy between supply side and actual requirements, they are bound to common practices and data availability:

> "The (food consumption) values are assessed through a commodity balance model and include household level and retail wastes. They are, therefore, not equal to actual food intake but are commonly used and well suited for cross-country comparisons . . . " (p. 4, [12])

> "Although these [dietary] data include wastes from processing, packaging, and transport, they do not include consumer waste and so do not correspond to the average consumed diet." (p. 13415, [27])

Indeed, supply-side data include retail and household level losses, which can be as high as one-third of the total supply for developed nations [12]. Moreover, registered food supply might be used as livestock feed [29].

It is problematic to (1) base assessments of "food demand and dietary requirements" on supply-side data and to (2) simplify population as the "number of people" when estimating availability or sufficiency. The first implies assessing resource requirements based on preferences and business as usual practices, including wasteful lifestyles, instead of assessing actual needs [30]. The latter neglects how different people from different ages, sex, birth cohorts, and body types have different food requirements. Both omissions might introduce a biased perspective when assessing the physical food needs of a particular year [31]. However, treating population as a number with static and homogenous requirements might have major implications when studying historical changes [12], forecasting scenarios [32], strategizing for food resilience [31], or monitoring progress toward sustainable development goals [21,33].

Based on standard methods, official statistics indicate global progress toward raising food consumption per person in the last three and a half decades, increasing from an average of

2370 kcal/person/day, to 2770 kcal/person/day [32]. However, given body-type changes, does a 30-year-old American male in 2014 require the same calories as his counterpart in 1974? Regarding demographic changes, do one million people representing the American population of 1974 collectively require the same calories as a similar representative sample in 2014?

Clarifying such questions is particularly important for assessing food requirements, which are not solely dependent on economic and technological factors, but are fundamentally a function of the energetic metabolic requirements of humans [34] depending on sex, age, weight, and physical activity level. The influence of these factors has been studied in individuals [35–37] and to a lesser extent at demographic levels [29,38,39]. Furthermore, most of the studies that are concerned with global food security overlook the effect of changes in the metabolic requirements of humans [24,32,40–42], and mainly focus on the technological aspects of food losses and waste [25,26].

The food-energy requirements of a person depend upon their biophysical characteristics, including age, sex, and weight [34]. For example, the food-energy needs of a male are generally larger than those of a female of the same weight and age. Similarly, people of the same sex but of different age and/or weight have different food-energy needs. Furthermore, people born in different generations—even in the same country—might have significantly different body configurations at a given life stage.

There have been increases in height [14] and body mass [16] between cohorts in the last century, both leading to increases in weight. Younger generations tend to be taller and heavier than older ones. Moreover, a worldwide aging phenomenon has been observed [19,43,44], particularly in developed nations. Both conditions, along with population growth [18], have repercussions for food demand. While weight increments lead to higher energy requirements, these requirements decrease with aging.

Thus, the society-wide food-energy requirements can be described as a function of both demographic and biological processes. The joint and independent effects of these drivers on food demand have not been systematically explored.

Few studies evaluated the food energy issue from a metabolic perspective at the global scale. Walpole et al. [39] studied the adult population (for the remainder of this paper, 'population' is used to denote 'adult population', unless otherwise specified) of 190 countries for the year 2005. Their results focused on the impact of obesity and showed that the energy requirements attributable to these factors corresponded to the energy requirements of 135 million global average adults. They also conclude that increasing cases of overweight and obesity could have an effect that is equivalent to the energy requirements of an extra half a billion people by 2050.

More recently, Hiç et al. [29] studied the energy requirements for 169 countries from a longitudinal perspective (1950–2050), including infants, children, adolescents, adults, elders, and pregnant and lactating women. The authors found that the average population's energy requirements increased in the past by 2.2% due to demographic structural changes, while using static average weight values. Although this study captures most of the demographic nuances of the human food requirements, it disregards the biophysical changes in height and BMI, which are proven to be the relevant factors for explaining changes in food demand. Thus, longitudinal food energy studies that account for these biophysical changes at the global scale are missing.

This article combines concepts from nutritional health sciences and demography, i.e., biodemography, with a dynamic stock modeling approach to deconstruct the role of population for food demand. It characterizes the implications of the biophysical heterogeneity of individuals and demographic transitions across nations and throughout time. The purpose is to clarify whether ignoring such aspects might—or not—lead to misrepresentations in food security assessments, forecasts, and scenarios.

This is the first study to deconstruct the role of human populations' physical characteristics from a longitudinal perspective, beyond mere population numbers, as a driver of global food demand. This article presents the integrated effect of changes of the individual biophysical traits of height, weight, and BMI and demographics on the human mass and food energy requirements of the population of 186 countries from 1975 to 2014. The results presented here are based on yearly sex-and-age disaggregated data for each country. In total, the dataset spans 114 birth cohorts.

2. Materials and Methods

This paper models population as a dynamic stock constituted by individual elements of diverse types whose size and characteristics change over time—either across generation or along their life. In other words, populations are composed of individuals of different ages and sexes whose characteristics change along their life and across cohorts; for instance, height, weight, life expectancy, and metabolic rate.

The methodical approach presented here is founded on the theory of demographic metabolism that was introduced by Lutz [45] to explain how societal changes result from the changing compositions of the population and its characteristics (e.g., sex, age, life expectancy, educational level, etc.). Some of these characteristics might change over the life of a person (e.g., educational level, age, body size) or generations (e.g., life expectancy, anthropometric features). Up until now, the demographic metabolism approach, despite a high degree of granularity when studying populations and data availability, has not been widely applied to address human needs or deconstruct the role of population as a driver of resource use.

The mathematical foundations of this paper are based on a "type–cohort–time" (TCT) approach, which is typically used to model resource use in the dynamic stocks of the built environment [46–48]. Here, a TCT approach is applied to investigate the changes in food-energy demand due to changes in the demographic structure and the biophysical characteristics of the world's population between 1975–2014.

Figure 1 presents a system and model definition for the study of the food energy demand "e" of the world's adults. The populations "P" of 186 nations "k" are modeled as a stock that is constituted of individual humans of different sexes (types) "i" and cohorts "c", whose biophysical characteristics and energy needs evolve over time "t". Particularly, the population stock is differentiated by sex and birth cohort, and the body mass index and height are used to estimate the caloric demand of individuals according to their sex and age. The SI describes the classical demographic modeling approach that was adapted in this research.

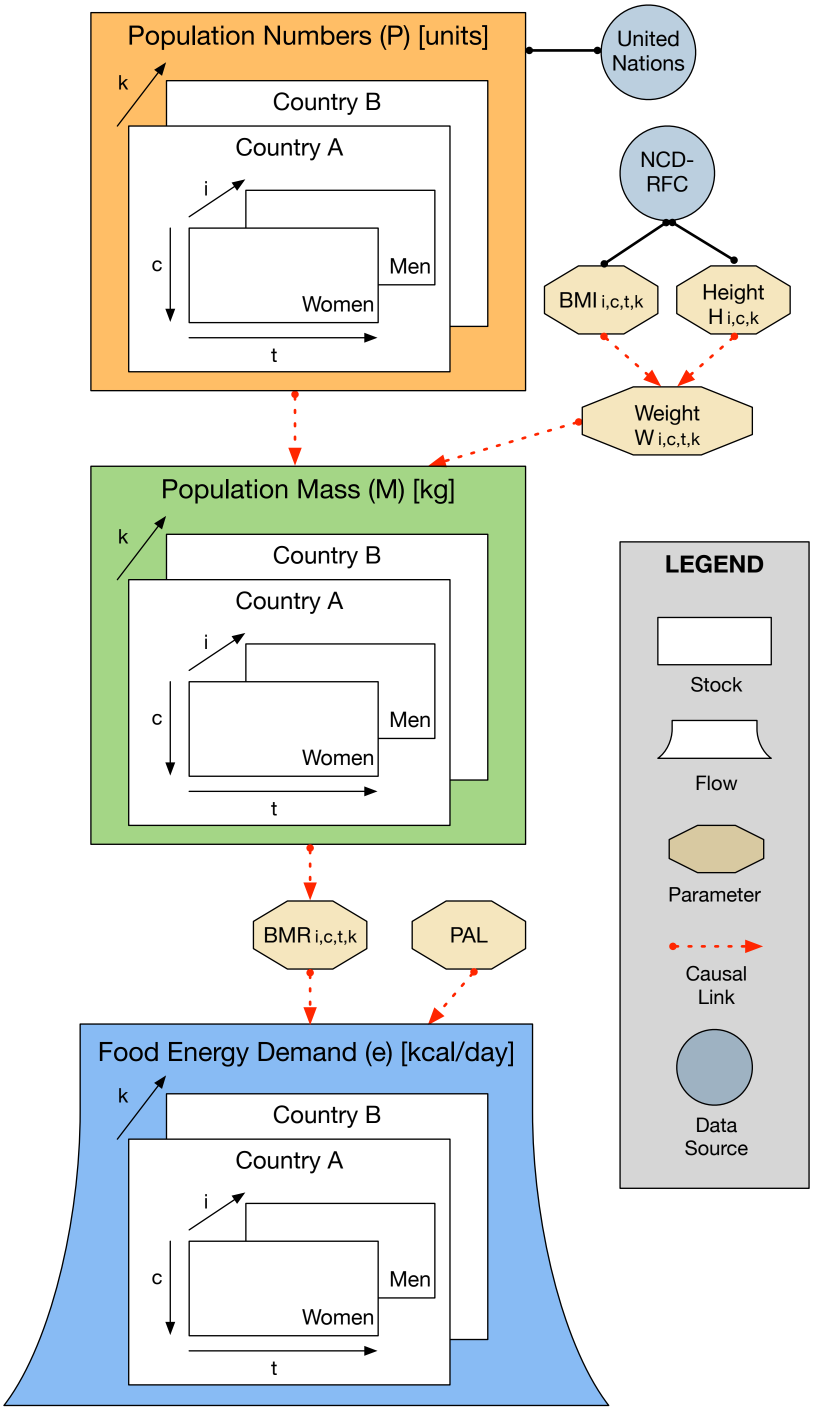

Figure 1. System and model definition for the study of the food energy demand of the population. "i" represent the sex, "c" the cohort, "t" the time, and "k" the country. NCD-RFC: Noncommunicable Diseases Risk Factor Collaboration (see references). BMI: Body Mass Index. BMR: Basal Metabolic Rate. PAL: Physical Activity Level.

2.1. Food Energy Demand Calculations

The calculations are based on the FAO guidelines [34] for total human energy expenditure to approximate the daily food energy "e" demand of a person (Equation (1)). First, the basal metabolic rate (BMR) is calculated as a function of weight "W", sex, and age with the guide's formulae on "Table 5.2" of the guidelines. Second, the average food energy need (theoretical energy expenditure) is estimated by multiplying the BMR by a factor of 1.76 to account for the physical activity level (PAL).

This is the average value in the FAO's guide (Table 5.1), which represents an "active or moderately active" lifestyle. A moderate activity level was assumed for all of the population, because specific PAL information is not available for most of the countries.

$$e_{i,c,t} = BMR_{i,c,t} \cdot \text{PAL} \tag{1}$$

Walpole's [39] considerations were followed to derive weight from BMI and height "H" (Equation (2)). BMI and height are taken from studies from the NCD-RFC (Noncommunicable Diseases Risk Factor Collaboration) [14,16]. The annual information on mean BMI, which is only available by sex, was assumed to be representative for adults of all ages. This allows the sex–cohort–time average weight calculations. In addition, the mean adult height, reported at the age of 21, was assumed to be achieved at the age of 18 for consistency with the BMI data, which reports from this age. Height data are available for the 1896–1996 cohorts; hence, adults from the 1875–1895 cohorts are considered to have the same height as their 1896 peers. The assumptions on height have a minor effect in the results and conclusions, as the population in the cohorts of concern represent a small share of the total population.

$$W_{i,c,t} = BMI_{i,c,t} \cdot H_{i,c}^2 \tag{2}$$

Average (per capita) values of food energy and weight at the national and global levels are weighted averages by population size, sex, and age. The total food energy "E" requirements and the total mass "M" (of a nation) aggregated the weight and energy demand of the individuals of all of the ages and sexes (Equations (3) and (4)).

$$M_{t,k} = \sum_i \sum_c P_{i,c,t,k} \cdot W_{i,c,t,k} \tag{3}$$

$$E_{t,k} = \sum_i \sum_c P_{i,c,t,k} \cdot e_{i,c,t,k} \tag{4}$$

2.2. Data Sources

Population statistics were obtained from the United Nations [49], which are available for every year of analysis by age groups of five years. For the 1975–1989 period, the data are available for 17 age groups covering the ages 0 to 80+. For the 1990–2014 period, the data are available for 21 age groups for the ages 0 to 100+. For every year of analysis, the age group's population was distributed equally among each individual age of the group. For the period 1975–1989 the 80+ population was apportioned among the ages 80 to 100+ by using the distribution of 1990. All of the input data that were used for the research are publically available as referenced within the paper, and made available for the reader as an Extended Data file.

3. Results

3.1. Global Trends

In the past four decades, the population increased by 116%, but was outpaced by increases of 146% in human mass and 129% in total theoretical food energy requirements (Figure 2a). The average global adult in 2014 is 14% heavier, 1.3% taller, 6.2% older, and has a 6.1% higher energy demand than the average adult in 1975 (Figures 2b and 3). From a global perspective, the effect of this additional demand is equivalent to the food energy needs of 286 million adults today. This is equivalent to about 1.2 times the population of United States, or double that of Brazil. The total mass increase due to additional weight was 39.68 Mton, which is the equivalent of almost the adult mass of India or two times that of the United States.

In 2014, the global population was 4.98 billion people, weighed 322 Mton, and demanded 13 Tkcal/day (Figure S1). Half of the population resided in only five countries: China, India, the

United States, Indonesia, and Brazil. These countries, when combined with Russia, represented 50% of the global human mass and food energy requirements. The world average adult weighed 64.7 kg, was 163 cm tall, was 42 years old, and demanded 2615 kcal/day, assuming a moderately active lifestyle [34] (Figure 3).

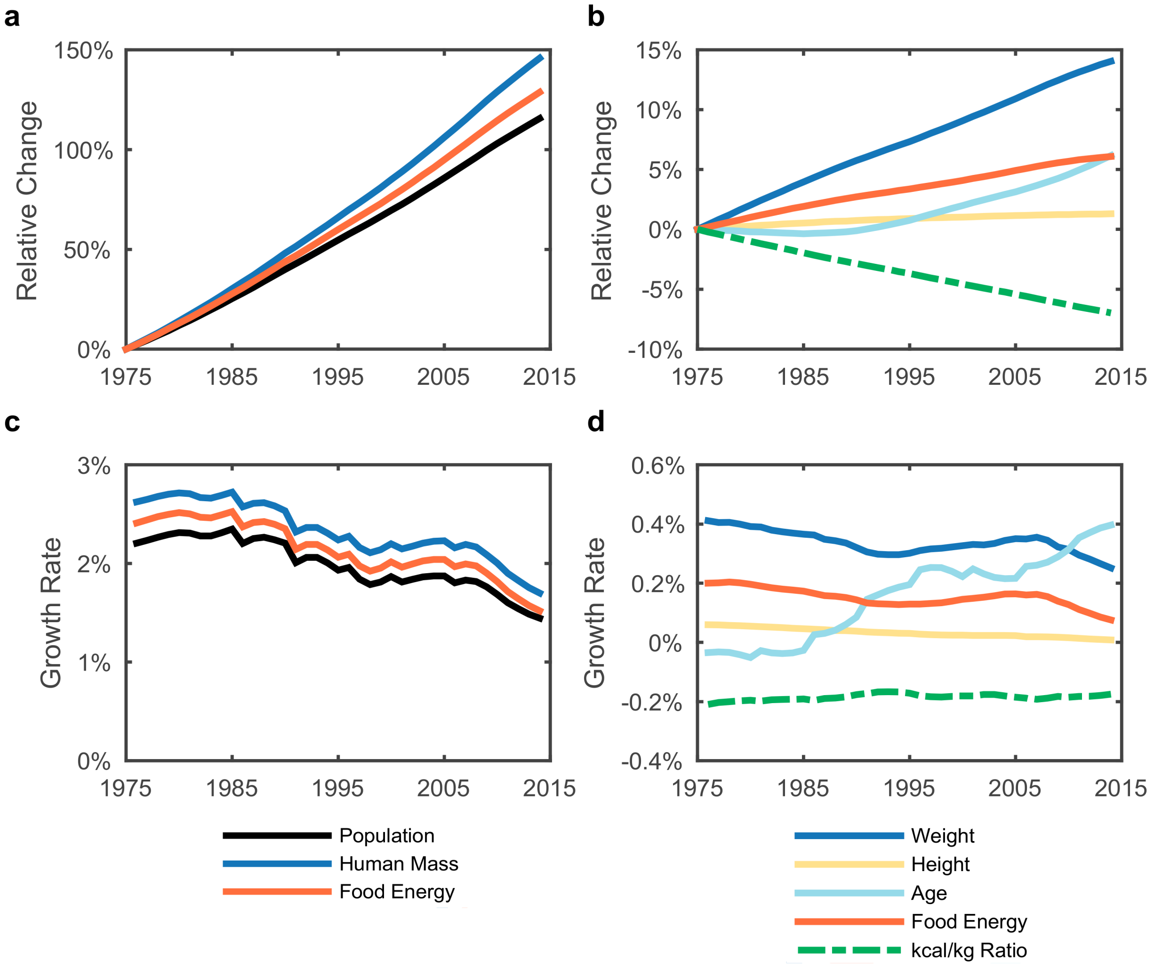

Figure 2. Changes in global population aggregate (left) and average biophysical traits (right). Relative changes (**a**,**b**) and growth rates (**c**,**d**) in population, human mass, and food energy (**a**,**c**) and weight, height, age, food energy, and energy-to-mass ratio (**b**,**d**) with respect to 1975. While human mass refers here to the total population, the term weight is used to indicate the average mass per capita. Key: Population, human mass, and energy grow at different rates. Human mass grows steeper than population (Left).

Population, human mass, and food energy grew at different rates (Figure 2c). The non-linear relationship between weight and food energy changes (Figure S2b) explains the continuous decoupling between weight gains and energy increases (Figure 2b). The food energy demand per kilogram of body weight (i.e., the energy-to mass ratio) decreased by almost 7%, from 43.4 kcal/kg to 40.4 kcal/kg. This implies a trend of diminishing returns i.e., for every kilogram of body weight increase, there was a reduction of 70 to 91 calories needed per every additional kilogram.

The total mass and energy growth rates declined between 1986–1998 and 2006–2014, generally following the population trend (Figure 2c). In addition, these periods were characterized by decelerations in weight gain and accelerations in aging (Figure 2d), which increased the decoupling between weight and energy. Since energy requirements tend to decline in the latter stages of life [34], aging mitigated the global surge in food requirements (Figure 4 and Figure S2d).

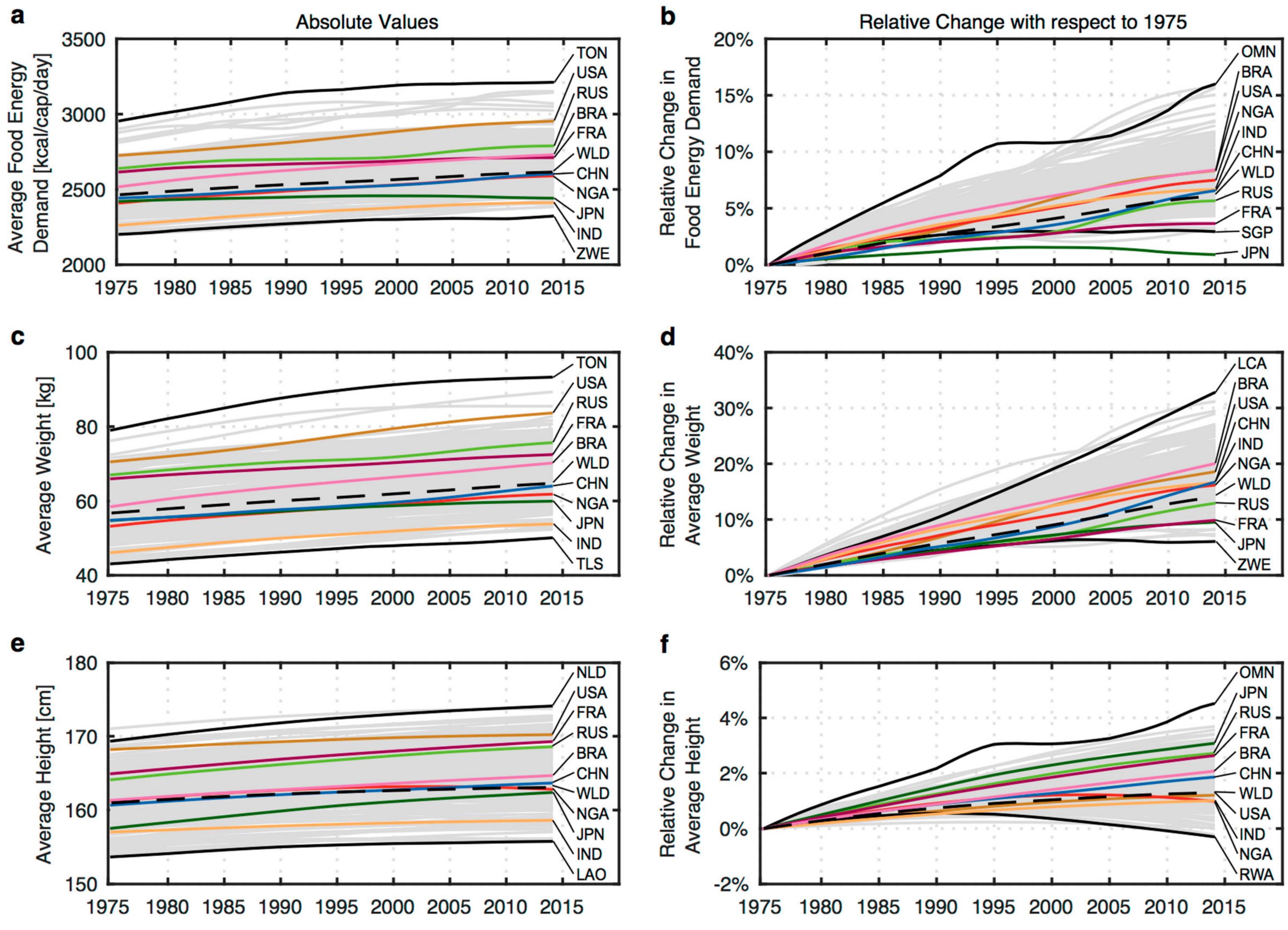

Figure 3. *Cont.*

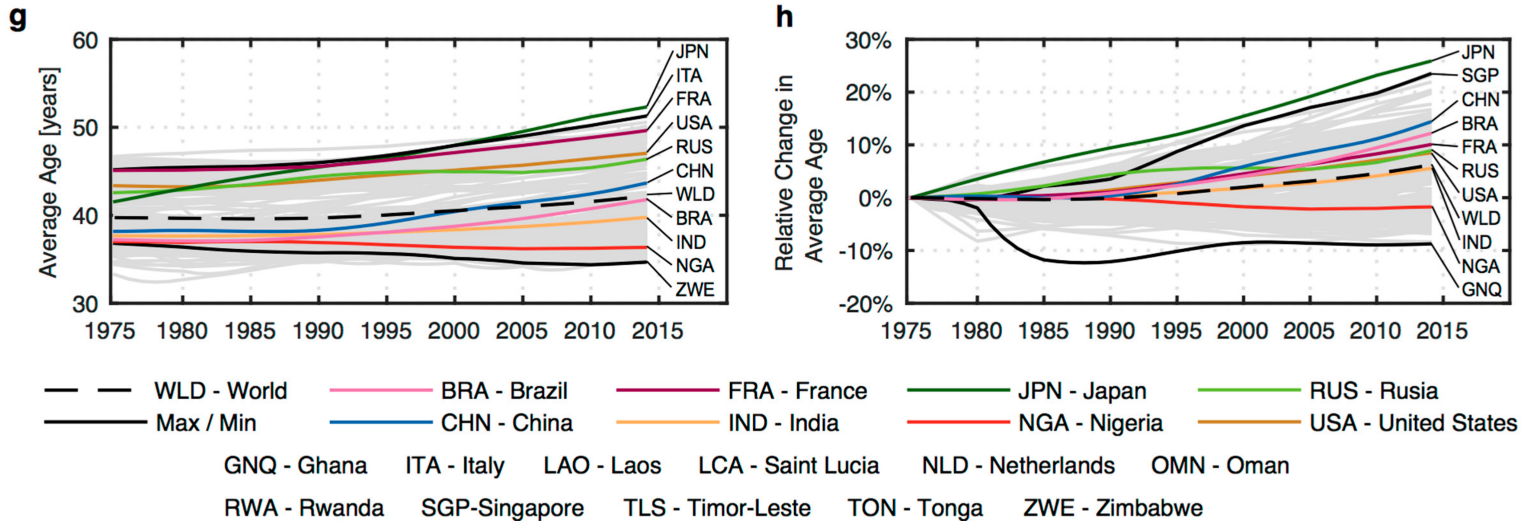

Figure 3. Absolute values (left—(**a**,**c**,**e**,**g**)) and relative changes (right—(**b**,**d**,**f**,**h**)) in average food energy demand (**a**,**b**), weight (**c**,**d**), height (**e**,**f**), and age (**g**,**h**).

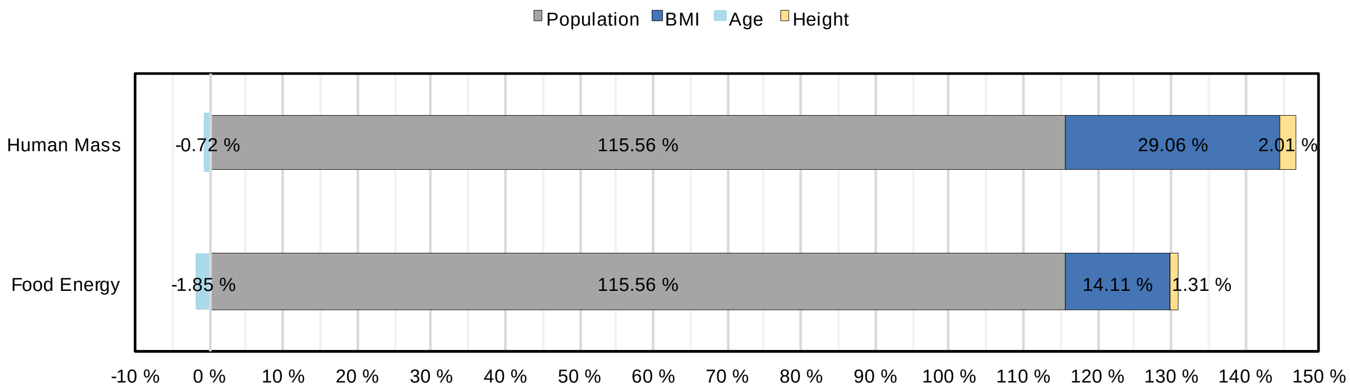

Figure 4. Decomposition analysis of factors contributing to changes in the total human mass and food energy in the period 1975–2014. Key: body mass index, reflecting weight gains, contributed to 14% of the increase in global energy.

The aging effect in the period 1975–2014 decreased food energy requirements by 1.9% (Figure 4), corresponding to the food needs of approximately 40 million adults, which is equivalent to the population of South Korea. Conversely, the rise in BMI increased the energy requirements by 14% in the same period (Figure 4). This is equivalent to the food needs of approximately 308 million adults, i.e., the combined population of Mexico and the United States.

In this study, the food energy requirements for the world average adult (2615 kcal/cap/day) are slightly higher than those of Walpole et al. [39] (2549 kcal/cap/day for 2005 adults) and Hiç et al. [29] (2370 kcal/cal/day for all the 2010 population). The difference between this study and that of Walpole et al. can be explained by the nine additional years that were included in this study, since our 2005 estimate of 2586 kcal/cap/day is similar to theirs (Dataset S1). The difference with Hiç et al. may be attributed to their inclusion of youths, which is a demographic with lower calorie requirements.

Hiç et al. [29] reported a 2.2% increase in average energy requirements between 1950–2010, while our estimates suggest a 6.1% increment between 1975–2014. Hiç et al. attributed the changes to demographic transitions toward older populations while recognizing the limitations of their approach in not including changes in weight. The results presented here depict the relevance of considering both weight and demographic structural changes when accounting for food energy, and demonstrate that changes in height and BMI have a larger impact than demographics (Figure 4).

3.2. National Trends

The average adult food energy needs and weight were in the range of 2200–2960 kcal/cap/day and 43–79 kg in 1975 (Figure 3a,c). These values increased to 2320–3210 kcal/cap/day and 50–93 kg in 2014 (Figure 5a,c). These gains ranged between 22–401 kcal/cap/day and 4–20 kg, with relative fluctuations of 0.9–16% for energy (Figures 3b and 5d) and 6–33% for weight (Figures 3d and 5b).

Notwithstanding this diversity, the disparity between the highest and the lowest energy requirements and the heaviest and the lightest adults has remained nearly constant since 1975. The adults with the highest energy demand require about 1.4 times more food energy than those with the lowest, and the heaviest weigh nearly twice as much as the lightest (1.86 times). Noteworthy, some of the highest and lowest increases coexist within Africa, Central Asia, and the Middle East, signaling the disparities between the countries of these regions.

Higher weight is usually correlated with higher energy demand; however, the countries with the most and least energy demanding adults do not strictly correspond to those with the heaviest and lightest countries (Table 1, and Dataset S1).

In 1975, the lightest (below 45 kg) and least demanding adults (below 2250 kcal/cap/day) were from the same countries (Table 1). However, in 2014, Ethiopia became one of the lightest (below 54 kg), yet was not among the least demanding (below 2300 kcal/cap/day). In contrast, Nepal remained among those with the lowest energy demand, despite a large weight increase (23.7%).

Adults in the Czech Republic, the United States, and Iceland were among the heaviest (above 70 kg), but did not have the highest energy demand (above 2800 kcal/cap/day) in 1975 (Table 1). Conversely, the United Arab Emirates and Qatar had some of the largest energy needs, but were not among the heaviest. Moreover, by 2014, Saint Lucia was the heaviest (above 81 kg), but not the most energy demanding. The countries with the highest energy-demanding population in 1975 remained so in 2014.

Also, the relative changes spanned a large range (Table 1). While Zimbabwe and Saint Lucia had the smallest and largest weight gains respectively, Japan and Oman had the smallest and largest energy increases, respectively (Figure 3b,d).

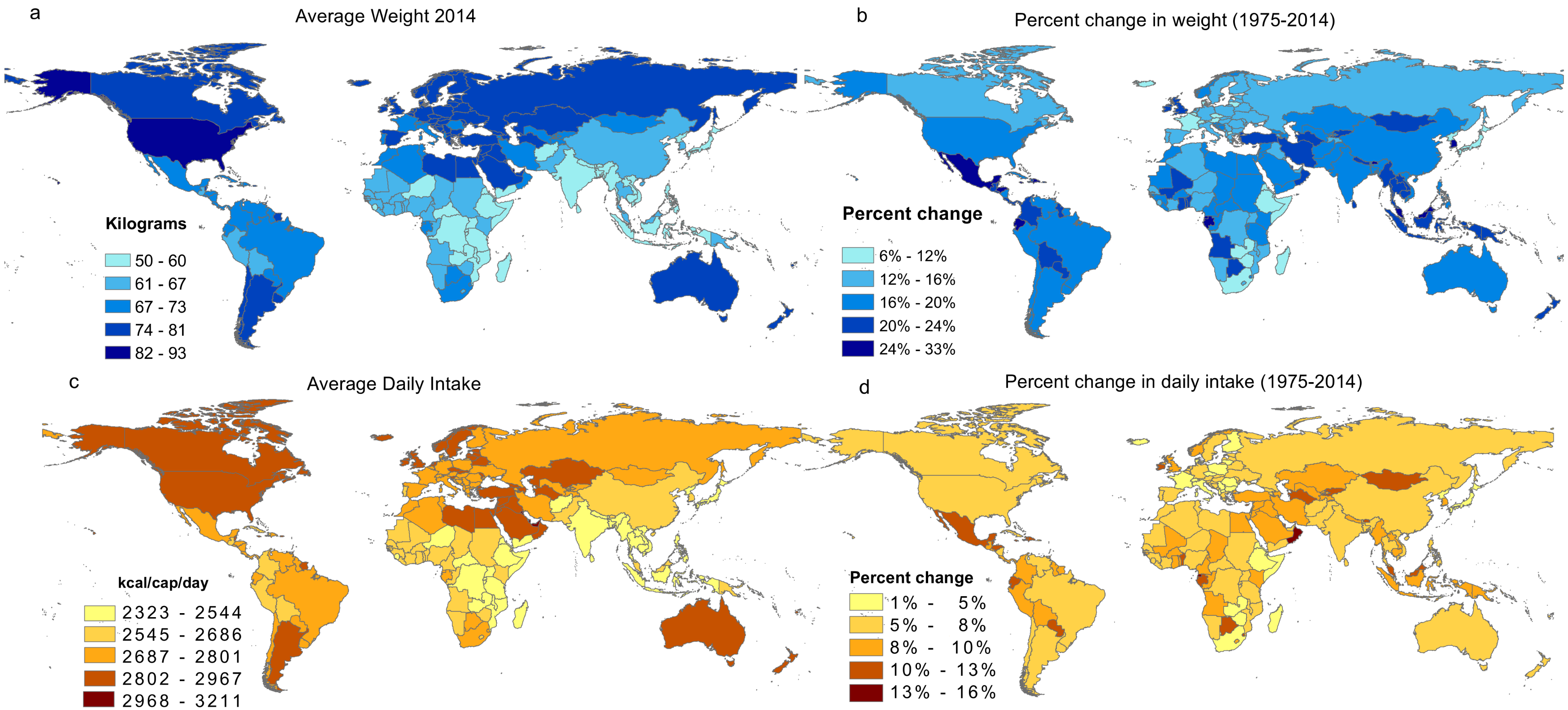

Figure 5. Average weight and food energy needs in 2014 (**a**,**c**) and relative change with respect to 1975 (**b**,**d**) by country. (**a**) Average weight in kg in 2014, and (**b**) relative change with respect to 1975 values. (**c**) Average food energy demand in kcal/cap/day in 2014, and (**d**) relative change with respect to 1975 values.

Table 1. Highest and lowest average food energy demand and weight.

Average Food Energy Demand [kcal/Cap/Day]				**Rel. Change in Food Energy**		**Average Weight [kg]**				**Rel. Change in Weight**	
1975		2014		**▲1975–2014**		1975		2014		**▲1975–2014**	
Highest 10											
TON	2955.8	TON	3211.4	OMN	16.0%	TON	79.1	TON	93.3	LCA	32.7%
PYF	2903.5	QAT	3151.3	GNQ	15.7%	PYF	76.2	WSM	89.3	GNQ	31.1%
ARE	2879.4	WSM	3143.6	LCA	15.6%	WSM	72.5	PYF	85.5	CPV	29.4%
QAT	2831.3	ARE	3070.9	CPV	15.0%	CZE	71.6	USA	83.6	MDV	28.9%
KWT	2830.9	PYF	3050.7	GRD	14.1%	KWT	70.7	LCA	82.7	MYS	27.0%
WSM	2812.4	KWT	3024.4	VCT	13.4%	USA	70.6	QAT	81.6	GRD	26.8%
ISL	2730.7	LCA	2966.8	JAM	12.7%	ISL	70.1	KWT	80.8	KOR	26.7%
CZE	2726.8	USA	2953.4	GAB	12.6%	LTU	69.6	NZL	80.6	JAM	26.3%
USA	2726.3	PSE	2949.1	KGZ	12.3%	ARE	68.9	AUS	79.3	VCT	26.2%
FSM	2707.3	JOR	2941.0	WSM	11.8%	EST	68.8	IRL	79.2	HND	26.0%
Lowest 10											
IND	2262.2	JPN	2441.8	CZE	4.4%	BDI	46.8	ERI	54.9	SGP	10.6%
BDI	2261.5	LAO	2430.0	MKD	4.3%	MMR	46.5	NPL	54.8	SOM	10.3%
MMR	2259.3	KHM	2420.7	MDG	3.7%	IND	46.1	LAO	54.6	CZE	10.1%
IDN	2243.8	ETH	2414.8	FRA	3.6%	IDN	45.5	KHM	54.4	FRA	9.8%
KHM	2230.7	NPL	2414.1	ZWE	3.3%	LAO	44.9	ETH	53.9	JPN	9.5%
LAO	2229.8	IND	2412.8	HKG	3.3%	KHM	44.8	IND	53.8	PRK	8.3%
NPL	2223.1	MDG	2402.7	DJI	3.2%	NPL	44.3	MDG	53.1	MDG	8.1%
BGD	2219.6	VNM	2384.4	PRK	3.2%	VNM	44.1	VNM	52.8	DJI	7.4%
TLS	2202.0	BGD	2384.1	SGP	2.9%	BGD	43.8	BGD	52.3	BHR	7.1%
VNM	2199.1	TLS	2322.7	JPN	0.9%	TLS	43.1	TLS	50.1	ZWE	6.1%

ARE: United Arab Emirates, AUS: Australia, BDI: Burundi, BGD: Bangladesh, CPV: Cape Verde, CZE: Czech Republic, DJI: Djibouti, ERI: Eritrea, EST: Estonia, ETH: Ethiopia, FRA: France, FSM: Federated States of Micronesia, GAB: Gabon, GNQ: Ghana, GRD: Grenada, HKG: Hong Kong, IDN: Indonesia, IND: India, ISL: Iceland, IRL: Ireland, JAM: Jamaica, JOR: Jordan, JPN: Japan, KGZ: Kyrgyzstan, KHM: Cambodia, KWT: Kuwait, LAO: Lao People's Democratic Republic, LCA: Saint Lucia, LTU: Lithuania, MDG: Madagascar, MKD: The Former Yugoslav Republic of Macedonia, MMR: Myanmar, NPL: Nepal, NZL: New Zealand, OMN: Oman, PRK: Democratic People's Republic of Korea, PSE: State of Palestine, PYF: French Polynesia, QAT: Qatar, SGP: Singapore, SOM: Somalia, TLS: Timor-Leste, TON: Tonga, USA: United States of America, VCT: Saint Vincent and the Grenadines, VNM: Vietnam, WSM: Samoa, ZWE: Zimbabwe.

The differences between weight and food energy trends can be explained by the differentiated height and age trends (Figure 3e,g). For instance, the French have a lower energy demand than the Brazilians (Figure 3a), despite being heavier and taller (Figure 3c,e). This may be explained by the older population in France (Figure 3g). Likewise, the Japanese and Indians now have similar food energy needs after marked differences in 1975 (Figure 3a). Food requirements remained almost constant in Japan, despite weight and height gains (Figure 3c,e), which may be explained by its population becoming the oldest (Figure 3g,h). On the contrary, the Indians' energy needs increased due to medium weight gains (Figure 3d) and moderate aging (Figure 3e,f). The discrepancy between weight and food energy is also explained by other environmental, lifestyle, and genetic factors [50,51].

Adults in all of the countries, except Madagascar and Rwanda, increased in average height (up to 4.5%) (Figure 3f), with height increases of up to 7.1 cm. However, some countries observed a decline in the average height after 1990 (Figure S3c). By 2014, 65 countries had declining average adult height, despite general increases in the mean height of individuals born in the last century [14]. Worldwide, height gains at the population level are slowing down, reinforced by the aging of the population. Generally, older adults, whose proportion in the population has been increasing, are shorter than their younger counterparts.

The changes in average population age exhibited the largest range (−8.8 to 25.8%) (Figure 3h), which translated to absolute age differences of −3.6 to 10.7 years. Yet, the aging of the population tends to accelerate in most countries [44] (Figure 3f,h and Figure S3).

4. Discussion

The results show higher energy requirements across nations (2320–3210 kcal/cap/day) than Hiç et al. [29] (1800–2800 kcal/cap/day) but are comparable to Walpole et al. [39] (2318–3017 kcal/cap/day). Despite these similarities, the ranking of the heaviest and lightest adults (Table 1), and thus food energy needs, differs slightly from the ranking made by Walpole et al. For instance, in the upper range, the average American (United States) and Emirati (United Arab Emirates) adult weighed 81.3 kg and 77.8 kg in 2005, respectively (Dataset S1). Walpole et al. reported 82 kg and 75.8 kg for the same countries. Similarly, the lower range results are 54.6 kg and 51.9 kg for Eritrea and Cambodia, while Walpole et al. reported 52.1 kg and 55.9 kg, respectively.

In terms of food energy requirements, 2920 kcal/cap/day were estimated for the United States, while Walpole et al. reported 2874 kcal/cap/day. This difference of 46 kcal/cap/day, although relatively small (approximately 1.5%), translates to a total of 10 Gkcal per day over the entire country. This energy demand is equivalent to the food energy requirements for Croatia or New Zealand, which each have approximately 3.4 million adults.

The differences between these results and Walpole et al. can be attributed to the dissimilar data sources and treatment. In this study, to derive weight, height data were available for all of the cohorts and sexes in all of the countries, but yearly BMI values were only reported as country averages by sex. On the other hand, Walpole et al. used BMI data grouped by age and sex. However, since some of the height data were missing, these data gaps were filled using linear regression methods of data from neighboring countries. Both methods can underestimate and overestimate the weight of different population segments as well as the country average. Thus, we highlight not only the need for, but also the importance of, having both historic age and sex disaggregated BMI information, as well as sex and cohort height statistics, to make better estimates on food requirements.

Kastner et al. identified "population numbers" as the major global driver of land requirements to satisfy food demand [12]. They concluded that with socioeconomic development, population growth rates decrease, and therefore per capita food availability increases [12]. This study shows that biophysical changes, especially weigh gains, are a significant driver for food demand in themselves. This means that a reduced population does not directly translate to increased food availability in linear terms, as previously assumed. Similarly, the resource implications of supplying adequate macronutrients and micronutrients might be underestimated if they rely on population numbers and supply data to estimate bottom–up nutritional needs [27,52]. Except for a few exceptional aging countries such as Japan, the same population size will likely require significantly more food energy in the upcoming decades, especially in the low-income and emerging economies (Figure 5).

Previous studies have either focused on food availability [12,29], biophysical changes [39], or demographic changes separately [17,44]. This study shows that combining these elements allows for "opening the black-box" of long-term drivers of food requirements. The paper contributes with a methodological framework for "bio-demographically informed resource assessments", which utilize existing public data (see Materials and Methods). The framework can be readily applied to other domains of consumption where larger body types and aging are expected to play a role: transport, clothing, furniture, housing, elderly services, etc.

Limitations and Strengths

Although this study provides clear findings, result interpretation is subject to data and methodological limitations. The United Nations (UN) population data are subject to underestimations and overestimations, especially in lower-income countries [29]. Yet, this is the only global database available, and it is widely used by the research community. There are currently no standardized global data on group-specific PAL across countries. A recommendation for international health statistics is to gather data on PAL differentiated by demographic group. This would increase the reliability of assessments for resource use, but also for social well-being [31,33].

This study excludes physiological or environmental considerations that might affect food requirements. However, such aspects might have stronger implications in the era of climate adaptation. This study identified increasing food demands without discussing health implications [52]. The estimated increased food requirements may very well correspond to increased obesity [39]. Fulfilling the demand estimates calculated from the bottom–up, as shown in this paper, would arguably reinforce overeating and further weight gains [29]. Arguably, given that the trends in obesity vary widely across countries with similar development status [15], overeating does not seem to be solely influenced by the amount of food available, but by the predominant lifestyles in a given nation.

Lastly, this article focuses on the basic aspect of food security, which is food availability, sufficiency, and with implications on food adequacy. However, issues of food access, utilization, and stability are important for food security, but lie beyond this research scope [31].

We combine three modeling approaches of traditional FAO food availability assessment, biophysical changes from the medical sciences, and demographic structural changes, as modeled by demographers. A necessary step is to characterize and quantify the effects of variables that were not previously examined in the light of resource demands. The type–cohort–time approach opens a path for dynamic stock models to move from merely describing the general characteristics of the total stock or certain cohorts, toward a more comprehensive and disaggregated description of the characteristics of its individuals, while still keeping account of the totality of the stock. This allows for more accurate descriptions of the populations and resources, which is key to enabling targeted policies that depart from defining the prerequisites for a good life, and depict strategies on how to provide them efficiently.

5. Policy Implications

This article broadens the perspective of food availability assessments by deconstructing and characterizing the influence of specific population traits beyond mere population numbers [12,23]. Methodologically, it increases the robustness and resolution of current approaches for food demand and availability. Although population size is commonly assumed as one of the main drivers of increased resource use, this paper shows how populations' biophysical characteristics exert their own inertia and evolve significantly over a short period of time.

More worryingly, top–down assessments of food sufficiency and malnutrition are commonly based on a comparison of average dietary energy requirements against food supply [31]. Monitoring progress would involve assessing differentiated energy requirements against the actual intake for each socioeconomic group [52]. Otherwise, the recent progress detected in rising food availability per person [32] might be actually undermined by the increased caloric demands.

For example, based on supply data, O'Neill et al. evaluated countries' food sufficiency by comparing country-specific supplied calories against a desirable threshold of 2700 kcal per adult per day [33]. Such a threshold value would perhaps been suitable for 1975, where energy demand ranged between 2200–2960 kcal/cap/day, but it certainly falls on the lower side for 2014 standards, which is between 2320–3210 kcal/cap/day. Further, given that average supply-side waste ranges between 214–510 kcal/cap/day, such a threshold value implies that around 2300 kcal/cap/day are available for consumption. That is even lower than the lowest bottom–up demand calculated here for 2014 (Timor-Leste).

Clearly, actual food availability should be set at a national level, correcting for body type, BMI, activity level, sex, and age distributions. Cross-validation of results across multiple sources increases the robustness of food security and availability assessments. The challenge is the lack of harmonized surveys across countries [31]. Thus, calculating energy needs by using anthropometric and demographic data is a pragmatic option to validate estimates of energy needs. It is a relatively low-cost procedure due to the availability of harmonized and reliable data sources, as has been demonstrated in this paper. At the individual level, the approach of this paper could improve social sciences research that estimates resources associated with lifestyles through bottom–up participatory methods or self-reported surveys [53].

Biophysical heterogeneity and demographic dynamics become increasingly relevant when exploring future scenarios of food security [32]. Given that growth in body sizes and population aging are expected to accelerate toward the mid-century [39,44], these phenomena have to be explicitly considered to ensure progress toward the Sustainable Development Goal of Zero Hunger. More robust assessments of food security are especially important for low-income and emerging economies, where most of the worlds' population live, and which currently experience the steepest sociodemographic transitions [18]. Future research could expand this work to model evolving cultural needs, such as diets or food preferences and characterize the bill of resources pulled by cultural lock-ins [54], and not only physical ones, as done here.

Addressing human needs in resource assessments calls for explicitly modeling the differentiated requirements of different population segments, and thus recognizing that society is an ensemble of diverse individuals from different generations who require different goods and services from the production systems along with their lives [54]. Furthermore, the increasing human mass, size, and aging phenomena have implications for resource use beyond food. Other energy and material connotations could be explored for buildings, transport, water, waste, sewage, furniture, clothing, and health care. Bigger humans tend to require larger living and sitting spaces and produce more waste [35], while an aging population requires different economic goods [5,19].

The implications of these findings also impact resource conservation strategies that argue for sufficient consumption by defining a desirable social threshold of food availability [30,33]. Ideally, international negotiations and national strategies toward reducing consumption would be based on bottom–up assessments of physical needs [54,55]. The risk of assessing supply while framing it as "demand" and modeling a static population might send imprecise messages to policies on food sovereignty and public health. In general, differentiating region-specific needs based on underlying physical drivers is a prerequisite toward feasible sufficiency thresholds [5,54]. Additionally, a more specific use of terminology i.e., not confounding the concepts of "food supply" and "food demand", or "food consumption" (purchased or eaten by households?) and "food intake" (theoretical or actual?) [12,27,33] could add transparency to food assessments.

In sum, this study highlights the importance of population dynamics and the differentiation of cohorts and types (see Materials and Methods) across time to better understand the changing needs of a population, as well as the resources and infrastructure that are required to satisfy these needs [54]. Integrated metabolic and sociodemographic models can contribute to a more robust global resource outlook [20] that can distinguish waste along the food value chain and forecast the food needs of evolving populations [29]. Based on current physical and demographic trends, feeding nine billion people in 2050 will require more total calories than feeding the same people today. This is a sobering fact that places further urgency on reducing supply chain and consumer waste, shifting to less resource-intensive diets, and encouraging more frugal and healthy lifestyles.

6. Conclusions

Indeed, the interrelated dynamics between population, weight, height, and age have implications for food supply and demand, as well as food security in the coming decades. This paper confirms that during the 1975–2014 period, the rise in food demand was mainly driven by population increases, even when considering country-specific energy requirements (116%). However, food demand was also affected in a non-negligible manner (13%) by changes in human biophysical traits (Figure 4), and only moderately counteracted by the aging phenomena at a global level (−2%). Thus, what previous analyses could have estimated as food surplus or waste might actually be sequestered mass—or energy required—by the bigger bodies of the human lot [56]. It is noteworthy that nations with an aged population can expect more drastic reductions in food demands due to the aging phenomenon. We show that the effect of biodemographic changes are cumulative and thus exert an inertia into the future. Based on the discovered trends, feeding nine billion people in 2050 will require significantly more total calories than feeding the same people today.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/10/10/3683/s1. Figure S1: Absolute values and relative changes in total adults' population, mass and food energy demand, Figure S2: Linear correlation analysis between relative changes in body mass index, weight, height, and age and relative changes in food energy demand, Figure S3: Growth rates in food energy demand, average weight, average height, and average age of adults, Dataset S1: Tables with population, and average food energy requirements, weight, height and age at the global and national levels. (as Excel file).

Author Contributions: F.V. conceived the study, gathered and processed the input data, developed the computer script, analysed results and drafted the manuscript. G.V. analysed results and drafted the manuscript. F.V. and G.V. contributed equally to the literature review, analysis of results, generation of figures and tables, and writing of the manuscript. D.B.M. contributed to the design and supervision of the study, and edited the manuscript.

Funding: The authors were funded by NTNU.

Acknowledgments: We thank Valentina Prado for insights, discussions, and critical reading of the manuscript. We thank Christine Hung for proofreading the article.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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Appendix: Supplementary Information

I. **Vita,G**.;Hertwich,E.G.; Stalder,K.; Wood,R. (2018) Connecting global emissions to fundamental human needs and their satisfaction. Environmental Research Letters.

II. **Vita, G**; Lundström, R; Quist, J.; Stadler, K.; Ivanova, D.; Wood, R. and Hertwich, E.G. Sustainable lifestyle scenarios to curb European environmental impact: Connecting local visions to global consequences (2018). Under review with Ecological Economics.

III. **Vita, G***. ;Ivanova, D*.; Dumitru, A.; García-Mira, R.; Carrus, G.; Stadler,K.; Krause ,K.; Wood, R.; Hertwich, E.G. The potential of grassroots initiatives to reduce carbon emissions and enhance well-being. (2018). Under review with Environmental Research Letters *Shared first authorship

IV. **Vita, G**.; Narasimha, R.; Usubiaga, A.; Min,J.; and Wood, R. The energy footprints of household durables, consumables and services: A global study from 1995 to 2011 (2018), in preparation.

V. Vásquez, F*.; **Vita, G***.; Müller, D. Food security for an ageing and heavier population (2018). Sustainability *Shared first authorship.

Supplementary Information

PAPER I

Connecting global emissions to fundamental human needs and their satisfaction

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Supplementary Information:

Connecting global emissions to fundamental human needs and their satisfaction

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Contents

1. Theories and concepts linking consumption and non-consumption to quality of life

The introduction in the main text describes three environmental sociology theories on development that link consumption, environmental impact and Quality of Life (QOL). Figure 1 (main text) summarizes the empirical relationships between consumption (or footprint) and QOL as predicted by the three theories. The table below is a further complement to the main text, where we present other related concepts and mechanisms from other disciplines that also support the predicted trends, but operate at different scopes.

Table 1 Summary of related concepts from other disciplines that align with trends between consumption and QOL and their respective theories of environmental sociology. Key: Theories in dotted box and gray background. Concepts in continuous box and white background. Concepts defined in Table 2 below.

Theories and concepts linking consumption and non-consumption to quality of life			
Trends / **Scope**	**Linear**	**Threshold (Saturating)**	**Non-relation**
Broad	Ecological modernization	Treadmill of production	Human ecology
	Neo-classical economics[1,2]: utility maximizing & rational choice[3,4]	Threshold hypothesis: limits to material well-being[5]	Ordinary consumption[3,6] and edited market choices[3,7]
Groups	Status-seeking: Conspicuous consumption[8] and symbolic consumption[3,9]	Status-seeking: Competitive consumption for status[3,4,10]	Social-exchange: Collaborative social systems of provision of satisfiers[4,11,12]
Individuals *Hedonic well-being*	Positional consumption[3,4] and subjective life satisfaction[13,14]	Hedonic adaptation[11,15] and rising material aspirations[14]	Psychological resilence[11,15,16]
Eudamoinic well-being	Satisfiers[12] and capabilities[17,18] that satisfy human needs	Defensive consumption[19,20] and pseudo satisfiers[12] that do not satisfy needs	Non-material satisfiers[12] that influence need satisfaction[3,4] e.g., Social dynamics
▢ (dashed) Theories	☐ Concepts and hypothesis supporting the expected trends at multiple scopes		

Table 2 Definitions of concepts and mechanisms that relate to each trend mentioned in the introduction and Figure 1 in the main text (see references 2,3,10,11,15,20 in main text for a review on the consumption-QOL links).

Linear trend: Consumption directly correlates with quality of life (QOL).
Rational choice: Individuals consciously choose goods to maximize their utility and QOL[21]. Assumption of mainstream economics. **Status gaining**: Conspicuous consumption is an evolutionary strategy to gain social status and thus QOL[3,10]. **Symbolic consumption**: Material goods have symbolic value beyond functionality. Identity and sense of belonging are socially constructed and communicated by symbols, including economic goods[9,22]. **Satisfiers:** Economic goods can contribute to need satisfaction[12]. Satisfiers can be material, such as books and computers for *understanding* or immaterial, such as observing nature or conversations can enhance *understanding*. **Capabilities:** Goods may provide capabilities to improve QOL[17,18] e.g., consuming electricity for cooking reduces health risks of indoor pollution and saves time[17,23]. However, capabilities can also be internal such as health or knowledge.
Threshold trends (Diminishing returns and saturation): Increased consumption has a waning or null effect on QOL.
Threshold hypothesis: The relationship between consumption and QOL plateaus once needs are satisfied[5]. A threshold is most obvious for physical needs such as nutrition, where excessive nutrients do not improve health. **Social comparison**: Seeking social status through consumption can divest resources from more rewarding purposes. If everyone does it, the relative social status remains the same while everyone is worse off[2,10]. Thus, it has been framed as a variant of the prisoners dilemma. **Hedonic adaptation**: People return to their original level of contentment once they get used to a new consumption level[11,15]. **Rising material aspirations**: As wealth and consumption rise, so do material aspirations[11,14]. Hence, people derive diminishing or null satisfaction from increasing consumption. **Defensive expenditures:** Expenses which are regrettably necessary to protect current satisfaction rather than increasing it[2,20]. They do not enhance QOL directly but as an intermediate consumption that might influence QOL[19,20] e.g. commuting to work or medical care. **Violating or inhibiting satisfiers**: Harmful goods that jeopardize or inhibit QOL[12] and typically have a contradictory effect. E.g., buying weapons increases the possibility of violence rather than safety, or excessive eating results in illness instead of health[24]. **Local pollution:** Consumption can directly threaten QOL due to local pollution and degradation of natural capital[19,25].
Non-relation (scatter, constant and outliers): QOL is stable or unaffected by consumption.
Ordinary consumption: Circumstantial purchases driven by habit, convenience, social norms or market offer are not intended to increase QOL[3,6]. **False satisfiers**: Goods that hold an empty promise to satisfy needs[12], e.g., education that does not enhance one's *understanding*[26]. **Non-market and human ecology factors**: QOL is affected by capabilities and satisfiers such as psychological health, climate, social exchange, nature, etc.[11,15,16,20].

2. Linking Market Goods to Human Needs

Max Neef Taxonomy of Human Needs.

Although Neef provides further examples in his works[12,24], the following table summarizes the taxonomy of needs which was the main guide to classify economic goods as satisfiers of needs (having and interacting) and to select indicators of need satisfaction (being and doing).

Table 3 The column of BEING registers attributes, personal or collective, that are expressed as nouns. The column of HAVING registers institutions, norms, mechanisms, tools (not in a material sense), laws, etc. that can be expressed in one or more words. The column of DOING registers actions, personal or collective, that can be expressed as verbs. The column of INTERACTING registers locations and milieus (as times and spaces). It stands for the Spanish ESTAR or the German BEFINDEN, in the sense of time and space. Since there is no corresponding word in English, INTERACTING was chosen afaut de mieux (Adapted from "Development and Human Needs"[12]).*

Need	Being (qualities)	Having (things)	Doing (actions)	Interacting (settings)
Subsistence	Physical health, mental health, equilibrium, sense of humour, adaptability	food, shelter, work	feed, clothe, rest, work, procreate	living environment, social setting
Protection	Care, adaptability, autonomy, equilibrium, solidarity	Insurance systems, savings, social security, health systems, rights, family, work	co-operate, plan, take care of, help, prevent	social environment, dwelling, living space
Affection	Self-esteem, solidarity, respect, tolerance, generosity, receptiveness, passion, determination, sensuality, sense of humor	friendships, family, partnerships, relationships with nature	Make love, caress, express emotions, share, take care of, cultivate, appreciate	privacy, intimacy, home, spaces of togetherness
Understanding	Critical conscience, receptiveness, curiosity, astonishment, discipline, intuition, rationality	Literature, teachers, method, educational policies, communication policies	Investigate, study, experiment, educate, analyses, meditate	Settings of formative interaction, schools, universities, academies, groups, communities, family
Participation	Adaptability, receptiveness, solidarity, willingness, determination, dedication, respect, passion, sense of humor	responsibilities, duties, work, rights, privileges	Become affiliated, co-operate, propose, share, dissent, obey, interact, agree on, express opinions	Settings of participative interaction, parties, associations, churches, communities, neighborhoods, family
Leisure	Curiosity, receptiveness, imagination, recklessness, sense of humor, tranquility, sensuality	Games, spectacles, clubs, parties, peace of mind	Day-dream, brood, dream, recall old times, give way to fantasies, remember, relax, have fun, play	Privacy, intimacy, spaces of closeness, free time, surroundings, landscapes
Creation	Passion, determination, intuition, imagination, boldness, rationality, autonomy, inventiveness, curiosity	abilities, skills, methods, techniques	Work, invent, build, design, compose, interpret	Productive and feedback settings, workshops, cultural groups, audiences, spaces for expression, temporal freedom
Identity	Sense of belonging, consistency, differentiation, self-esteem, assertiveness	Symbols, language, religions, habits, customs, reference groups, sexuality, values, norms, historical memory, work	Commit oneself, integrate oneself, confront, decide on, get to know oneself, recognize oneself, actualize oneself, grow	Social rhythms, everyday settings,, settings which one belongs to, maturation stages
Freedom	Autonomy, self-esteem, determination, passion, assertiveness, open-mindedness, boldness, rebelliousness, tolerance	equal rights	Dissent, choose, be different from, run risks, develop awareness, commit oneself, disobey	Temporal/spatial plasticity

Development of identity matrix between economic goods and needs

The first group discussion was held as an informal workshop led by the first author and attended by the co-authors. The goal was to propose an initial 0-1 correspondence matrix between market goods and the needs they might satisfy. Disagreements on this correspondence were discussed and resolved by consensus, illuminating discussions with supporting material containing definitions and applications reported by Max Neef et al[12,24,27]. The second round consisted on the validation of the proposed matrix by two external colleagues and one student where they register their approval or disapproval with respect to the original proposal and explained their view[28]. The third round consisted of the main authors consolidating the disagreements from round 1 and 2. Resolving it by the establishing an exhaustive and mutually exclusive reasoning behind each correspondence (Table 4). This final matrix and reasoning was reviewed and commented by two external reviewers form the DESIRE project consortium. In this way, the initial correspondence matrix between goods and needs was established as step 1 in Table 2 of the main text, stated in the Appendix and available in the Supplementary Data file. For example, sanitation services could not be related to any other need than subsistence and protection.

Table 4 *Exhaustive and mutually exclusive criteria behind each link between economic goods and fundamental human needs*

Air mobility	Mobility (aerial): They do not fulfill subsistence (enabling to collect food, work, etc.). However, they do fulfill leisure (travel for entertainment, sports, etc.), creation (enable for networking, workshops, co-create) and freedom (save time and provide spatial-temporal plasticity).
Broad category	Broad category relates to freedom of market and choice.
Clothing	Clothing: Basic expenditure is for subsistence, discretionary expenditure goes to identity.
Clothing, household materials	Clothing: Basic expenditure is for subsistence, discretionary expenditure goes to identity. Leather fulfills some creation when used for handcrafts or other household work.
Construction materials	Construction materials: provide basic shelter, health and safety (protection) but people also create spaces (creation)
Electricity	Electricity provides basic shelter and protection but also enables creation, leisure and freedom.
Food	Food: basic for survival but also reflects individual lifestyle and social identity.
Gov defense and social security	Protection related services
Health	Health and medical related items :subsistence and protection
HH materials mix	Mixture between shelter and non-shelter materials for household.
Household fuels	Household fuels: They are part of subsistence as they provide shelter in the broad sense. They are also part of protection since they provide a decent living (heat and sanitation) and they facilitate cooking and household works (creation) and enable freedom of time.

Household materials	Household materials: Can to be used for household work as basic shelter (subsistence), creation (household productive activities) and identity (clothing).
Housing	Basic shelter subsistence and protection
Non-air mobility	Mobility (non-aerial) : They fulfill subsistence (enabling to collect food , work , etc.) ,leisure (travel for entertainment, sports, etc.) , creation (enable for networking, workshops, co-create) and freedom (save time and provide spatial-temporal plasticity)
Non-air mobility status	We make a distinction between transport capital (vehicles) and the fuel. The fuel choices normally does not reflect identity, but the purchase of vehicles does reflect identity.
Non-shelter household products	Non-shelter household products : Manufactured products which are not primordial to subsistence but are related to creation household production) and freedom (to choose between alternatives and buy time saving goods)
Paid domestic work	Particular case of inputs for household work. Related to social status and to saving time.
Protection related services	Protection related services
Research and Development	Understanding
Synergistic satisfier: community	Synergistic satisfier. Related to participation but to many other needs as well similar to drivers behind voluntary work. Protection as in "co-operate and take care of", understanding as in "educate" , participation " become Affiliated", leisure “relax play, have fun" creation as in” work, and invent, cultural groups and workshops”. Identity as in "integrate oneself, belonging"
Synergistic satisfier: education	Mainly satisfier for understanding but also corresponds to social identity and status.
Synergistic: hotel and restaurant	Leisure is satisfied in hotels and restaurants. Hotels enable spatial plasticity and restaurants save time (freedom) and provide food (subsistence).
Tobacco	Smoking as identity and leisure
Waste treatment	Waste treatment: Enables subsistence by not polluting the environment and provides protection (sanitation).

The chart below summarizes the result of linking goods to needs. The y-axis shows the total consumption in goods associated to each need. The x-axis shows the approximate share of market goods that relate to each need.

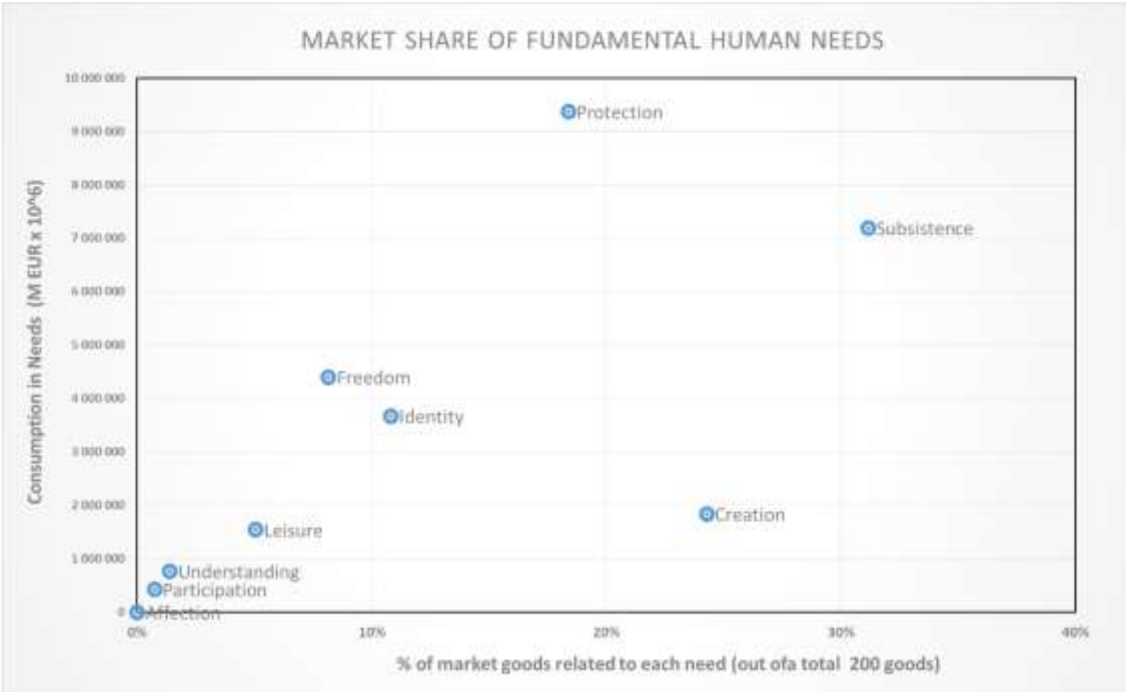


Figure 1 Global market consumption for each need in M EUR (y axis) and amount of goods associated to each need (x axis), out of 200 goods and services.

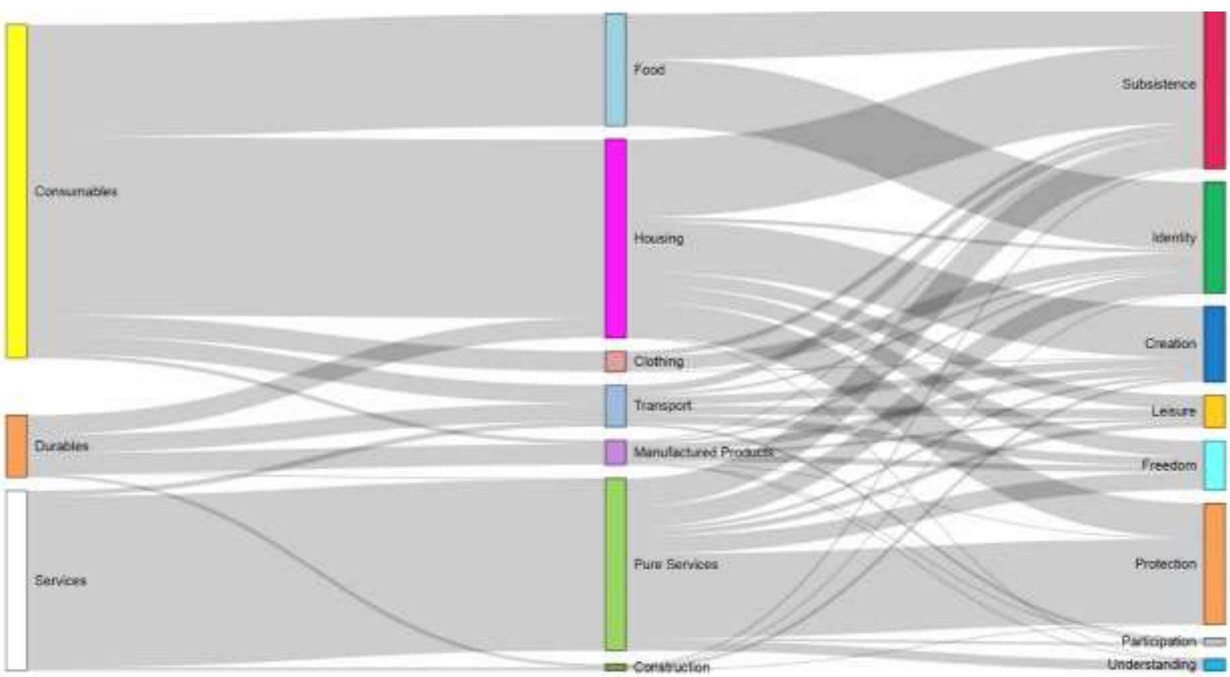


Figure 2 The global energy footprint of human needs under different classifications of goods. Results represent global final consumption by households, governments and non-profit serving households in 2007. The global carbon footprint embodied in consumption for 2007 amounts to 265 Exa-joules (EJ). The figure displays the links between three different aggregations of the 200 market goods in EXIOBASE3 by type of consumer good, classified as durable goods, non-durable goods and services (left), by consumption category or functionality (middle)[29] and by human needs they satisfy[24] (right). The equivalent figure for carbon footprint is available in the main text. 117 EJ were contained in the direct operational energy used by households, which are not reflected in the diagram but are considered for the rest of the paper.

Table 3 Inter-relationships between different product categories expressed in percentage of total global energy flows (265 Exajoules for year 2007)

Contributions and relationships between different product categorizations expressed in percentage of total net energy. The energy embodied in the consumption of households, governments and non-profits serving households amounted to 26.4 Exajoules in									
Categories	Clothing	Construction	Food	Manufactured Products	Transport	Pure Services	Housing	**Totals**	
Durables	0%	1%	0%	4%	3%	0%	3%	**11%**	
Consumables	4%	0%	20%	1%	3%	0%	31%	**58%**	
Services	0%	1%	0%	0%	1%	30%	0%	**31%**	
Totals	**3.5%**	**1.1%**	**19.5%**	**4.3%**	**7.2%**	**29.9%**	**34.4%**	**100.0%**	
Categories	Subsistence	Protection	Understanding	Participation	Leisure	Creation	Identity	Freedom	**Totals**
Clothing	1%	0%	0%	0%	0%	0%	2%	0%	**4%**
Construction	0%	0%	0%	0%	0%	1%	0%	0%	**1%**
Food	8%	0%	0%	0%	0%	0%	12%	0%	**20%**
Manufactured Products	0%	0%	0%	0%	1%	1%	0%	1%	**4%**
Transport	1%	0%	0%	1%	2%	2%	1%	2%	**7%**
Pure Services	5%	15%	2%	0%	1%	1%	4%	3%	**30%**
Housing	13%	6%	0%	0%	2%	9%	1%	3%	**34%**
Totals	**29%**	**21%**	**2%**	**1%**	**6%**	**13%**	**19%**	**9%**	**100%**

Concordance matrix between market goods and human needs

The Supplementary Data file presents a full concordance matrix, following the reasoning above. The quantitative partitions following US consumer expenditure survey ratios[30] is described in the main text. Subsistence (S), Protection (PR), Affection (A), Understanding (U), Participation (Pa), Leisure (L), Creation (C), Identity (I), Freedom (F). Concordance matrix is also available as a supplementary data file.

Monte Carlo uncertainty test of concordance matrix

To characterize the uncertainty in our concordance matrix we use a Monte Carlo simulation to test al possible allocations between market goods and needs, for those goods that relate to more than one need.

<u>Detailed description</u>

Let **N** be a binary correspondence matrix of consumer goods (all products *p* in the MRIO system) to human needs (*h*) than the randomised proportion matrix **R** is given by:

$$r_{i,j} = \frac{x * n_{i,j}}{\sum_i (x * n_{i,j})} \qquad \begin{array}{c} i = \{1, \dots, p\} \\ j = \{1, \dots, h\} \\ x \in X \sim \text{unif}([0,1]) \end{array}$$

We assume that consumers attempt to satisfy the same human need irrespective of if the bought product is produced domestically or imported. Therefore, the randomized proportion matrix is spanned over the full final demand vector for a specific country *c* out of the full set of countries *d* ($c \in d$). This is than multiplied with the consumption final demand vector **f** of country *c* (household final demand, non-profit organizations serving household and expenditures by government). This than gives the final demand **y** per human need satisfaction category *j* for each country *c*:

$$\mathbf{y}_j^c = \left(\mathbf{1} \otimes \mathbf{r}_j^c\right) \cdot \mathbf{f}^{\mathbf{c}} \qquad \begin{array}{c} j = \{1, \dots, h\} \\ c = \{1, \dots, d\} \end{array}$$

Where ⊗ denotes the Kronecker product, · element wise multiplication (Hadamard Product) and **1** specifies a column vector of 1's of size *d*.

The final footprint calculations for each consumption vector per country and human need satisfaction category followed the standard consumption based accounting framework [31,32]. The randomisation and footprint calculation was repeated for each of the 10,000 Monte Carlo runs.

Practical example

Assume that the consumer product *Motor vehicles* could potentially serve as satisfier for subsistence, participation leisure, creation, identity and freedom. The specific row in the correspondence matrix would be:

Consumer good	Subsistence	Protection	Affection	Understanding	Participation	Leisure	Creation	Identity	Freedom
Motor Vehicles	1	0	0	0	1	1	1	1	1

In each Monte Carlo run, a random number was assigned to each human need satisfaction category representing to which degree *Motor Vehicles* are bought in an attempt to satisfy the specific human need. The random numbers were scaled to add up to one to ensure that total final demand add up to the given final demand in one country. Some potential randomised values are given below:

Monte Carlo run for Motor Vehicles	Subsistence	Protection	Affection	Understanding	Participation	Leisure	Creation	Identity	Freedom
Run 1	0.5	0	0	0	0.1	0.1	0.1	0.1	0.1
Run 2	0	0	0	0	0	0	0	1	0
Run 3	0.3	0	0	0	0.2	0.5	0	0	0
….									
Run 10 000	0.1	0	0	0	0.1	0.2	0.2	0.1	0.3

Results of uncertainty test

Based on these values, total final demand was scaled and footprints were calculated for each human needs satisfaction category. Due to the long calculation times, we restricted the analysis of the Monte-Carlo approach to the Carbon Footprint. The results of the Monte Carlo runs reveal s the spread of the probabilistic value for the carbon footprint of each need. The hierarchy of needs with respect to CF does not change. We also find that our partitions values using quintile inequality expenditure data lie within the spread shown by the Monte Carlo. Similar to our results in the main paper, a probabilistic test shows that Protection and Subsistence as the Human Needs with the highest Greenhouse Gas (GHG) emissions. Creation, Freedom, Identity and Leisure cause somewhat lower emissions with some overlap between the results given by the different runs. The lowest GHG emissions are connected to the satisfaction of Participation and Understanding.

By testing all possible allocations, we find the same relative hierarchy of the needs' carbon footprints and our values fall within the interquartile range of dispersion. We find an uncertainty range of about 0.5 Gt CO2 eq for identity, understanding and participation and about 1 Gt for the rest (95% Confidence Interval).

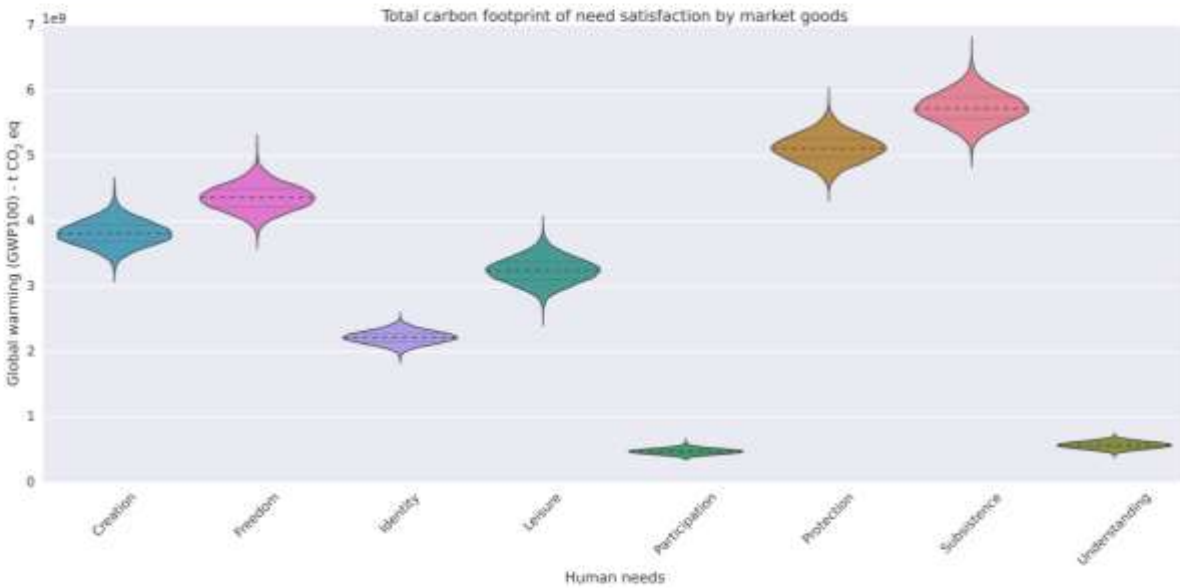


Figure 3. Violin plots displaying the dispersion resulting from a Monte-Carlo test for uncertainty of using US expenditure data to split synergistic satisfiers. Dotted line indicates median, continuous line indicate quartiles 1 and 3, extremes indicate low values of the Kernel Density Estimate.

3. Environmentally Extended Multiregional Input-Output model (EXIOBASE3)

Consumption, energy and carbon footprints of needs

Consumption footprints attribute all upstream emissions and resources to the final consumer of a good. In this sense, the impact of a nation equals the direct impact occurring in households plus the embodied impact from all purchased goods, including imports and excluding exports [33]. Thereby considering all the energy and carbon emissions embodied in the production of goods. We use the standard Leontief Input-Output model [31] to calculate consumption energy and carbon footprints as follows:

$$x = (I - A)^{-1} y \qquad (1)$$

Where x represents the total economic output of a given sector in a given nation as a function of the final demand *y* of the consuming nation. *I* is the identity matrix, and *A* is the technical coefficient matrix, representing the inter-industry requirements. $(I\text{-}A)^{-1}$ denotes the so-called Leontief Inverse *L*, the matrix of total requirements. The footprints are calculated by including the inputs and emissions embodied in goods:

$$FP = sLy + F_{hh} \qquad (2)$$

Where L is the Leontief Inverse, the matrix of total industrial requirements. The environmental coefficients$s$ are obtained by dividing the total energy or emissions associated to the production of a given good by its economic output (i.e. TJ/EUR or CO_2 eq/EUR). F_{hh} represents direct household emissions and energy from transport, heating and cooking fuels. Only embodied emissions were considered for global Sankey diagrams direct households emissions are considered for the footprints of needs across nations. We consider the final consumption (y) of households, governments, and non-profit institutions serving households[34–36].

We used EXIOBASE3, an open-access Environmentally Extended Multiregional Input-Output database [37], to model global economic activity and resources in 2007. We calculated carbon footprints by using the Global Warming Potential metric to normalize both combustion and non-combustion greenhouse gases (CO_2, CH_4, N_2O and SF_6) to equivalent amounts of CO_2 by weighting their radiative forcing over a time horizon of 100 years. Direct methane emissions from livestock were accounted for but emissions from land use change are not reported in the database[34]. We use total greenhouse gas emissions from all sources except the Intergovernmental Panel on Climate Change (IPCC) category Land Use, Land Use Change and Forestry, and apply IPCC 2007 characterization factors for aggregation of different GHG into carbon dioxide equivalents (CO2-eq) GWP100. For further details, we refer to Wood and colleagues [34]. The energy footprints includes 74 different primary and secondary energy carriers used by industries for the production of goods. The energy footprint reported here is "Net Energy Footprint", which is equal to final energy plus transformation losses. Net energy refers to the end use of energy products less exports of energy products plus all losses of energy (i.e. during extraction, transformation, storage and distribution)[38]. The net energy use accounts build for this paper are largely based on the approach documented in the supplementary material of Stadler et al. (2017)[39]. Thus, the extended energy balances of the International Energy Agency[40,41] are first converted from the territory to the residence principle (see [42] for more details). From the resulting dataset we calculate the product- and flow-specific net energy use as defined above and allocate energy consumption to EXIOBASE industries and products using the same allocation approach as in Stadler et al. (2017)[39]. For further details about the energy accounts see[43–45].

EXIOBASE3 covers the 44 large economies, which make up 91% of global GDP and 65% of the world population [34]. The rest of the countries are aggregated into five "Rest of the World" regions representing Middle East, America, Europe, Asia Pacific and Africa. A global carbon footprint of needs is only considered for the first section of results (figures 2 and 3 and table 5). Only the 44 individual countries were considered for the analysis of need satisfaction (figures 4a and 4b and table 4).

Elasticities

By applying the concept of consumption and footprint elasticity [29,35], we were able to evaluate changes in the consumption and FP of needs resulting from changes in total consumption of households, governments and NPISH. Elasticity, ε, and measures the percentage change in the dependent variable (FP or consumption) of each human need with respect to a 1% rise in the total consumption:

$$\varepsilon = (\partial f_i/\partial y)/(f_i/y) \qquad (3)$$

Where y represents per capita yearly expenditure and f represents the stressor, consumption or footprint, of each need $\boldsymbol{i}$. By applying natural logarithmic transformation to equation 3, we calculated a set of univariate regressions for each stressor, where **a** and **ε** are constants, and **u** is the error term:

$$\ln f_i = a_i + \varepsilon_i \ln y + u_i \qquad (4)$$

When ε=1, the dependent variable (footprint or consumption) changes equally to the change in total expenditure (see SI). Values of ε below 1 indicate that the consumption or footprint of a need increase less than total expenditure while values above 1 indicate the opposite: greater relative increases in need consumption or footprint with respect to total consumption. Expenditure elasticities have been interpreted as the needs that are to be prioritized as consumption rises [29,35]. Footprint elasticities simply indicate the marginal increases in impact with respect to consumption.

Online Resources for EXIOBASE3

Stable version of EXIOBASE3 for the year 2007 should be downloaded and referenced as follows:
http://exiobase.eu/index.php/data-download/exiobase3

Pymrio is an open source tool for Environmentally Extended Multi-Regional Input-Output (EE MRIO) analysis developed in Python.
It provides a high-level abstraction layer for global EE MRIO databases in order to simplify common EE MRIO data tasks.
https://zenodo.org/record/1154787#.Wo12lBZG1O8

Tutorial on how to download and perform computations with EXIOBASE
http://pymrio.readthedocs.io/en/latest/notebooks/working_with_exiobase.html#Getting-EXIOBASE

The only exogenous file to EXIOBASE to calculate the footprints of needs is the products to needs concordance matrix, available both as appendix and supporting data file.

4. Quality of life indicators: justification, limitations and interrelations

Reasoning behind Indicator choice

The reasoning behind the choice of indicators was largely based on the examples provided by Max-Neef[12,27], specially for the dimensions of "being" and "doing" (SI Table 3). The dimensions of "having" and "interacting" were mainly used to inform which type of goods could be satisfiers of given needs[12]. When Neef's guidelines were insufficient to make a sensible choice of indicator, we referred to the relevant literature in psychology and social indicators, as described below. To assess the satisfaction of a specific need we compiled indicators by following a triad principle i.e. we prioritize including three indicators that measure the same dimension of a need with indicators of different nature (subjective, values and objective) in order to obtain robust conclusions on the satisfaction- footprint relationship. For example, we were able to apply this principle to *Participation* (democracy index, subjective satisfaction with democracy, importance of democracy), *Leisure* (leisure time, leisure satisfaction and importance of leisure), *Creation* and *Freedom* (see appendix).

The motivation behind combining different indicator types follows the notions towards assessing human needs satisfaction directly and through multiple dimensions[11,46]. Objective indicators prove useful to track the degree of social progress and associated resources, while subjective indicators inform the satisfaction of people with respect to the achieved progress[46,47]. Assessing policy success in terms of subjective satisfaction can better focus interventions and save resources. If objective circumstances do not match subjective experiences, it might indicate inadequate satisfiers or access. For multi-dimensional needs, the discrepancy across indicators may inform which dimensions require special attention.

The following section provides justification for the indicators chosen in this study. We further discuss strengths, weaknesses, alternatives and potential overlaps. We present a correlation analysis across indicators of need satisfaction to warn about potential spurious patterns. However, correlations between subjective and objective indicators can indicate convergence (or mismatches) between human satisfaction and objective circumstances, which is also a point of this study.

Subsistence

The taxonomy of needs suggests *subsistence* as highly related to living standards and basic biological functions (SI table 3). Accordingly, we chose indicators of subjective health, living standards and fertility and survival rate. When choosing indicators for *subsistence*, it is important to consider the average wealth of the sample. Since our database includes nations from the middle to high-income spectrum, there are not considerable differences in indicators such as life expectancy or immunization rate. Thus, we chose children survival and inverse fertility rates to represent a more vulnerable group of society and their chances to survive, which showed more variation than life expectancy. Healthy life expectancy would also have been a reasonable choice[47] but was overlooked early in the analysis. Healthy life expectancy would be better comparison for the subjective good health indicator. In any case, indicators on health status are necessary to assess *subsistence* satisfaction, since good health is a satisfier of *subsistence* (SI table 3). The OECD has also pointed to the importance of inquiring about subjective health[48] beyond objective indicators of health provision. Given the development status of the sampled nations, we expected low variability when assessing an objective measure of material living standards. We consider the subjective satisfaction with respect to living standards to be more indicative of the human experience of how well means meet ends in a given country.

Correlation test: *subsistence*

We only find a weak correlation (below 0.5 Pearson correlation coefficient) between child survival and subjective living standard. Negative correlation between good health and inverse fertility rate, and positive between living standard and good health. Child survival and the inverse fertility rate are strongly correlated, as expected.

Subsistence indicators		Good health	Standard of living	Child survival rate
Good health	Pearson Correlation	1		
	Sig. (2-tailed)			
	N	40		
Standard of living	Pearson Correlation	.555**	1	
	Sig. (2-tailed)	0.000		
	N	40	44	
Child survival rate	Pearson Correlation	-0.078	.363*	1
	Sig. (2-tailed)	0.637	0.017	
	N	39	43	43
Inverse Fertility Rate	Pearson Correlation	-.344*	-0.097	.731**
	Sig. (2-tailed)	0.030	0.533	0.000
	N	40	44	43

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Protection

Protection is especially multi-dimensional. According to Neef, it is satisfied through dwellings, living spaces, curative systems, health systems, personal security, insurances, etc[12] (SI table 3).To measure objective satisfaction with dwelling and adequacy of living space we used access to infrastructures (sanitation, modern fuels and electricity). Beyond enabling decent living[49], these infrastructures have also been proven to enable protection of health due to reduced indoor pollution or personal safety (public lighting)[23,50].

For subjective measures of satisfaction with living spaces, we assess the affordability of housing. A good objective contrasting indicator would have been material poverty (% of expenditure in housing), but many countries do not report this indicator.

To measure objective and subjective personal safety we followed the choices by the OECD[48] and Social Progress Index[51]. We use Homicide rate and perception of safety. Homicide rate is perhaps not good measure given the sample of countries, where homicide is relatively low and thus low variability is expected. Initially we used crime statistics as a measure for *protection*, but decided to exclude it, since it seemed to reflect the efficiency of law enforcement rather than prevalence of crime e.g. Sweden appeared more dangerous than South Africa. This is another consideration behind indicator choice: even if the indicator is available, often it might not be reliable for the research question. To measure objective and subjective health, we use obesity rates and the satisfaction with quality of health care quality. There are many other epidemic diseases that could have been chosen[52] to assess health. We chose obesity since it is more indicative of health within middle to high-income nations. Satisfaction with health care quality should reflect the feeling supported by the curative systems. All of which are mentioned by Max-Neef (SI Table 3).

To assess financial safety, we used long-term employment rate to be compared with subjective satisfaction with the local labor market. This, however, does not inform about how well remunerated jobs are and whether salaries meet ends. Concrete indicators on the actual disposable income and cost of living could make a good complement to measure financial safety.

Correlation test: *protection*

Indicators of access to infrastructure (sanitation, modern fuels and electricity) logically have a strong correlation among them, as they all deal with infrastructures. Similarly, the feeling of safety correlates with a low probability of being murdered. Health care quality and feeling safe correlate with each other and they both correlate with affordable housing, long-term employment, inverse homicide rate and access to sanitation. Feeling safe correlated with non-obese adults which in turn negatively correlates with sanitation and modern fuels, signaling the association between obesity and modernity.

Protection Indicators		Health care quality	Feeling safe	Satisfaction with local labour market	Affordable housing	Non-obese adults	Long-term employ ment	1-homicide rate	Access to sanitation	Access to modern fuels	Access to electricity
Health care quality	Pearson Correlation	1									
	Sig. (2-tailed)										
	N	44									
Feeling safe	Pearson Correlation	.701**	1								
	Sig. (2-tailed)	0.000									
	N	44	44								
Satisfaction with local labour market	Pearson Correlation	0.021	0.077	1							
	Sig. (2-tailed)	0.893	0.619								
	N	44	44	44							
Affordable housing	Pearson Correlation	.433**	.393**	-.337*	1						
	Sig. (2-tailed)	0.004	0.009	0.027							
	N	43	43	43	43						
Non-obese adults	Pearson Correlation	0.064	.340*	-0.163	0.248	1					
	Sig. (2-tailed)	0.678	0.024	0.291	0.108						
	N	44	44	44	43	44					
Long-term employment	Pearson Correlation	.512**	.404**	-0.158	0.217	0.166	1				
	Sig. (2-tailed)	0.001	0.009	0.325	0.174	0.298					
	N	41	41	41	41	41	41				
1-homicide rate	Pearson Correlation	.389**	.632**	0.012	0.158	.334*	0.096	1			
	Sig. (2-tailed)	0.009	0.000	0.940	0.312	0.026	0.552				
	N	44	44	44	43	44	41	44			
Access to sanitation	Pearson Correlation	.396**	0.254	-0.003	0.226	-.389*	-0.032	.322*	1		
	Sig. (2-tailed)	0.009	0.104	0.987	0.149	0.011	0.844	0.038			
	N	42	42	42	42	42	40	42	42		
Access to modern fuels	Pearson Correlation	0.120	-0.042	-0.074	0.021	-.523**	-0.121	0.042	.868**	1	
	Sig. (2-tailed)	0.443	0.787	0.636	0.894	0.000	0.450	0.790	0.000		
	N	43	43	43	43	43	41	43	42	43	
Access to electricity	Pearson Correlation	0.205	0.269	0.083	0.028	-0.268	-0.047	.384*	.698**	.669**	1
	Sig. (2-tailed)	0.187	0.082	0.598	0.860	0.083	0.769	0.011	0.000	0.000	
	N	43	43	43	43	43	41	43	42	43	43

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Subjective Protection and Subsistence

Interestingly, standard of living is correlated with both subjective good health and also satisfaction with the quality of health care. On the other hand, satisfaction with local labour market seems to be associated with less affordable housing.

Subjective Protection and subsistence		Good health	Standard of living	Satisfaction with local labour market	Affordable housing	Health care quality	Feeling safe
Good health	Pearson Correlation	1					
	Sig. (2-tailed)						
	N	40					
Standard of living	Pearson Correlation	.555**	1				
	Sig. (2-tailed)	0.000					
	N	40	44				
Satisfaction with local labour market	Pearson Correlation	-0.109	-0.100	1			
	Sig. (2-tailed)	0.502	0.517				
	N	40	44	44			
Affordable housing	Pearson Correlation	0.216	.360*	-.337*	1		
	Sig. (2-tailed)	0.187	0.018	0.027			
	N	39	43	43	43		
Health care quality	Pearson Correlation	.337*	.742**	0.021	.433**	1	
	Sig. (2-tailed)	0.033	0.000	0.893	0.004		
	N	40	44	44	43	44	
Feeling safe	Pearson Correlation	.323*	.685**	0.077	.393**	.701**	1
	Sig. (2-tailed)	0.042	0.000	0.619	0.009	0.000	
	N	40	44	44	43	44	44
**. Correlation is significant at the 0.01 level (2-tailed).							
*. Correlation is significant at the 0.05 level (2-tailed).							

Creation Indicators

We were able to implement the “triad principle” by measuring “creativity” through objective, values and subjective indicators. Neef states that *creation* is satisfied by inventing, building, skills, work, imagination, etc. (SI Table 3). The Global Creativity Index includes measures of human capital and innovation (SI appendix). While the subjective measure is more broadly a judgement of the freedom to use one’s full creative potential at formal work. The value indicator measures the importance to be able to use one’s full creative potential. Although we found the measure appropriate, improvements could be done by assessing household production, informal work and creative leisure to provide a more comprehensive and inclusive picture of the satisfaction of *creation*.

Correlation test: *creation*

We find a weak but significant correlation between subjective satisfaction creativity at work and global creativity index, indicating convergence between objective circumstances and subjective experiences.

Creation		Satisfaction with creativity	Importance of creativity	Global creativity index
Satisfaction with creativity	Pearson Correlation	1		
	Sig. (2-tailed)			
	N	37		
Importance of creativity	Pearson Correlation	0.314	1	
	Sig. (2-tailed)	0.066		
	N	35	39	
Global creativity index	Pearson Correlation	.634**	-0.081	1
	Sig. (2-tailed)	0.000	0.631	
	N	36	38	43
**. Correlation is significant at the 0.01 level (2-tailed).				

Freedom Indicators

We were able to implement the "triad principle" by measuring *freedom* from objective, values and subjective perspective.
Institutional Freedom, being a function of personal rights, tolerance and inclusion might conceptually overlap with the democracy index, which includes political rights (see *participation* below). The measure chosen for freedom aligns with the proposal by Neef (SI Table 3). We would expect institutional freedom to translate into subjective satisfaction of personal freedom and higher values. Given the abstract nature of *freedom*, we are satisfied with our choices for subjective indicators. However, indicators that assess the satisfaction regarding temporal and spatial plasticity (SI Table 3) could provide a more complete view.

Correlation test: *freedom*
We find a strong correlation between institutional freedom and its subjective appreciation and importance. Suggesting convergence between objective circumstances, personal experiences and expectations for freedom.

Freedom		Freedom to choose	Importance of freedom	Institutional freedom
Freedom to choose	Pearson Correlation	1		
	Sig. (2-tailed)			
	N	43		
Importance of freedom	Pearson Correlation	0.159	1	
	Sig. (2-tailed)	0.377		
	N	33	34	34
Institutional freedom	Pearson Correlation	.653**	.561**	1
	Sig. (2-tailed)	0.000	0.001	
	N	42	34	43

**. Correlation is significant at the 0.01 level (2-tailed).

Identity
We use income equality as an objective measurement of *identity* following findings that claim equal societies are crucial for the development of self-identity [53]. Instead, inequality fosters identities created out of cultural compliance or imposed by class distinction (minorities, defensive identity, etc.)[54,55].

Neef suggests that authenticity is a satisfier of *identity* [24] (SI Table 3). A common psychological definition of "authenticity" refers to the attempt to live one's life according to the needs of one's inner being, rather than the demands of society or imposed by early conditioning. We chose the only cross-country indicator (SI appendix) that found fitting to the proposed scale for authenticity [56]. We understand the feeling of authenticity to be a proxy for satisfaction with self-identity rather than socially constructed identity.
The prevalence of self-expression values in society indicate the importance that a society gives to human choice and agency. It is an indicator of the collective appreciation of individual expression and self-determination. The higher the self-expression values, the less *identity* is shaped by external factors or social expectations. A high score favors human autonomy and intrinsic motivation to be and do according to ones self-imposed aspirations[55].
Correlation test: *identity*
We do not find significant correlations between the indicators of *identity* satisfaction.

Identity		Authenticity	Self-expression	Income equality
Authenticity	Pearson Correlation	1		
	Sig. (2-tailed)			
	N	30		
Self-expression	Pearson Correlation	0.317	1	
	Sig. (2-tailed)	0.088		
	N	30	43	
Income equality	Pearson Correlation	0.153	0.294	1
	Sig. (2-tailed)	0.418	0.056	
	N	30	43	44

Leisure

We are able to follow the triad principle for leisure by comparing objective free time, to the subjective leisure satisfaction and the value of leisure.

The drawback of calculating "objective free time" based on working hours is that it does not consider household work or other kind of endeavors, which are not necessarily *leisure*. The advantage of the subjective question is that it captures the general time affluence/scarcity that people experience. This triad signals the importance of measuring the same concept through different indicators to find convergence or mismatch across indicators.

At early stages, we considered to measure *leisure* through indicators about socializing or satisfaction with work-life balance. Although interesting, values were missing for some countries.

Correlation test: *leisure*

Similar to freedom, we find significant positive correlations between subjective satisfaction of leisure and objective available free time as well as the importance of leisure. Meaning these indicators converge.

Leisure		Leisure satisfaction	Importance of leisure	Residual free time
Leisure satisfaction	Pearson Correlation	1		
	Sig. (2-tailed)			
	N	42		
Importance of leisure	Pearson Correlation	.495**	1	
	Sig. (2-tailed)	0.001		
	N	39	41	
Residual free time	Pearson Correlation	.516**	.417*	1
	Sig. (2-tailed)	0.002	0.014	
	N	34	34	36
**. Correlation is significant at the 0.01 level (2-tailed).				
*. Correlation is significant at the 0.05 level (2-tailed).				

Understanding

Understanding is satisfied through formal and informal education (SI Table 3). The drawback of using the education index is that is only informs about the years of formal schooling but not about the effectiveness nor the actual skills developed. Naturally, individuals without formal schooling could also have a deeper understanding of issues based on own experiences or autodidactic study. The two subjective indicators chosen to assess *understanding* are of similar nature (SI appendix) and yet yield different results i.e. people tend to educate themselves linearly with increased emissions, but their evaluation of gained knowledge reaches a threshold. We believe the subjective indicators chosen are a good proxy for the satisfaction of *understanding*. However, a better objective indicator could be based on cognitive capacities or other direct measure (functional reading) rather than the years of schooling. Other possible indicator that we had considered for subjective satisfaction is "the importance of science in daily life" but deemed normative to equal valuing science to *understanding*. We chose "learn new things in life" as an indicator for master, as done by previous studies [16].

Correlation test: *understanding*

We find moderate and strong correlations for all the indicators of *understanding*, even if the trends with respect to footprints are not the same. Interestingly, the satisfaction with learning new things in life correlates with satisfaction with the subjective appreciation of education quality but not so with objective measures. Interestingly, reading comprehension level in the country does trend with subjective and objective satisfaction with formal education.

Understanding		Learn new things in life	Education Quality	Education Index	PISA
Learn new things in life	Pearson Correlation	1			
	Sig. (2-tailed)				
	N	38			
Education Quality	Pearson Correlation	.558**	1		
	Sig. (2-tailed)	0.000			
	N	38	44		
Education Index	Pearson Correlation	0.244	0.150	1	
	Sig. (2-tailed)	0.139	0.331		
	N	38	44	44	
PISA - Reading comprehension	Pearson Correlation	0.218	.306*	.401**	1
	Sig. (2-tailed)	0.202	0.049	0.008	
	N	36	42	42	42
**. Correlation is significant at the 0.01 level (2-tailed).					
*. Correlation is significant at the 0.05 level (2-tailed).					

Participation

We chose indicators of democracy to assess satisfaction with *participation*. Although Neef does not explicitly suggest democracy as a satisfier for *participation* (SI Table 3). The state of democracy reflects the opportunity for people to engage in their in political and communitarian affairs. The quality of democracy reflects gender equality, political rights, freedom of speech, access to economy and health , freedom of movement, self-organization and association[51,57]. All of which are satisfiers for civic engagement[12,53,57,58]. The democracy index is of "higher quality" in the sense that it takes multi-dimensional approach to democracy by including characteristics of the political system (50% of the weight) but also the performance of the non-political dimensions[58] (gender 10%; economy 10%; knowledge 10%; health 10%; and environment 10%.)[58]. The subjective indicators of satisfaction and values indicate how people feel about their current democratic systems (SI appendix). The drawback being that the indicators are framed as ruling democracy and do not consider non-political aspects. A more comprehensive assessment of *participation* would include indicators of political agency, civil organizations, civic engagement, stakeholder dialogues, etc. These might not be available across nations.

Correlation test: *participation*

Interestingly, we find significant correlation between the subjective satisfaction with current democracy and the importance of democratic rule but not with the objective democracy index. This indicates that as people feel more satisfied with their political system, they tend to value it more. The correlations also suggest that democracy is more important in countries where democracy prevails, indicating that values match objective reality in this case.

Participation		Satisfaction with democracy	Importance of democracy	Democracy index
Satisfaction with democracy	Pearson Correlation	1		
	Sig. (2-tailed)			
	N	35	33	
Importance of democracy	Pearson Correlation	.549**	1	
	Sig. (2-tailed)	0.001		
	N	33	38	
Democracy index	Pearson Correlation	0.277	.334*	1
	Sig. (2-tailed)	0.118	0.046	
	N	33	36	42
**. Correlation is significant at the 0.01 level (2-tailed).				
*. Correlation is significant at the 0.05 level (2-tailed).				

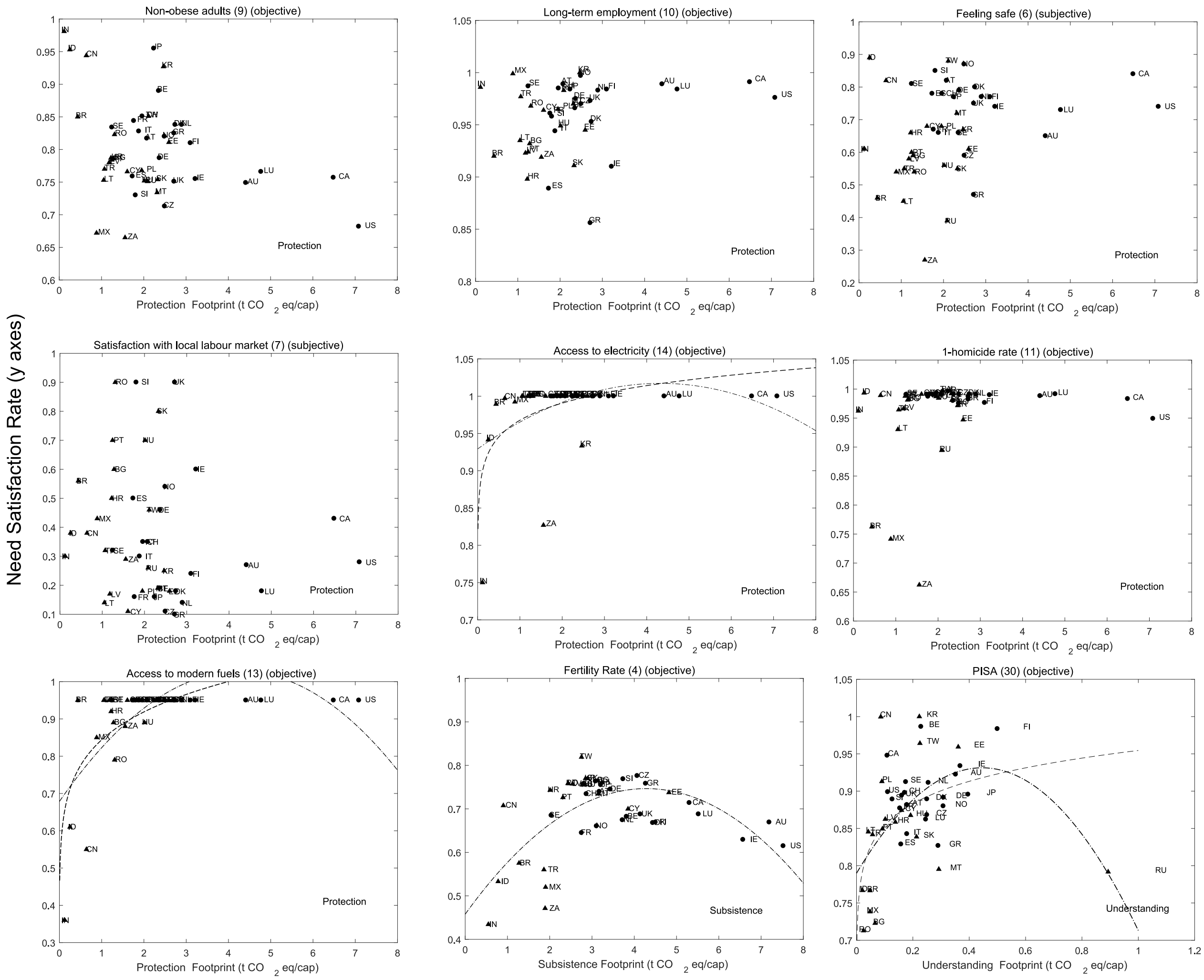
Subjective Satisfaction: correlations

Except for the satisfaction with democracy and authenticity. Most other indicators of subjective satisfaction correlate with each other: subjective learning, freedom to choose, creativity and self-expression. Satisfaction with democracy does correlate with freedom and learning, while authenticity correlated with creativity and leisure. Interestingly, all need satisfaction correlate positively and strongly with overall life satisfaction.

Subjective satisfaction		Satisfaction with democracy	Satisfaction with creativity	Freedom to choose	Authenticity	Leisure satisfaction	Self-expression	Learn new things in life
Satisfaction with democracy	Pearson Correlation	1						
	Sig. (2-tailed)							
	N	35						
Satisfaction with creativity	Pearson Correlation	0.314	1					
	Sig. (2-tailed)	0.080						
	N	32	37					
Freedom to choose	Pearson Correlation	.557**	.564**	1				
	Sig. (2-tailed)	0.001	0.000					
	N	34	37	43				
Authenticity	Pearson Correlation	0.268	.556**	0.255	1			
	Sig. (2-tailed)	0.177	0.001	0.174				
	N	27	30	30	30			
Leisure satisfaction	Pearson Correlation	0.190	.605**	.428**	.502**	1		
	Sig. (2-tailed)	0.288	0.000	0.005	0.006			
	N	33	35	41	28	42		
Self-expression	Pearson Correlation	0.312	.658**	.469**	0.317	.387*	1	
	Sig. (2-tailed)	0.068	0.000	0.002	0.088	0.012		
	N	35	37	42	30	41	43	
Learn new things in life	Pearson Correlation	.530**	.488**	.603**	0.373	.524**	.451**	1
	Sig. (2-tailed)	0.002	0.003	0.000	0.055	0.001	0.004	
	N	31	34	38	27	36	38	38
Overall life satisfaction	Pearson Correlation	.567**	.647**	.760**	.472**	.424**	.652**	.557**
	Sig. (2-tailed)	0.000	0.000	0.000	0.008	0.005	0.000	0.000
	N	35	37	43	30	42	43	38

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).



Supplement of Figure 4 (main text): **Plots excluded in panel in the main text.**

5. Supplementary discussions

Unweighted regressions

The decision against presenting population-unweighted results lies in our research question and on the characteristics of our sample. Mainly, our sample does not include enough individual nations to justify population weighting and neither to derive insights about global trends. As we present in figure 3 in the main text, the BRICS nations concentrate the largest portion of the population in our sample. In this case, we think that weighting by populations would introduce more noise and skewedness than benefit.

Further, our question is whether the likelihood of satisfaction of a need given need is related (or not) to the consumption of goods that potentially satisfy that need. This means that our results are generalizable to individual countries [47] and not to global populations [59]. In this sense, we test the level of satisfaction Y in a given nation with respect to the carbon footprint X in the same nation. As discussed in detail elsewhere

[59,60], weighting observations by populations is more suitable to describe global patterns with respect to resource efficiency. Thus, population weights have been used to interpret changes at the global level or by world regions [61] and more to forecast future absolute levels of resource use [62] In that case, it would certainly make more sense to regress Luxemburg and China with weights since changes in Luxemburg would hardly affect the global outcome in terms of satisfied people. In our case, we are interested in per capita consumption as an indicator of input and do not try to predict the total footprint at a global level. In our case, we normalize footprints per capita and regress against satisfaction level as it has been done for this type of research [47].

Life satisfaction

We use Overall life satisfaction as a general indicator of QOL to compare with previous literature. However, the debate around the best fitting model[13,14,47,63,64] downplays the limitations of life satisfaction as an indicator of QOL. First, it does not inform about specific needs. Second, life satisfaction indicators face inherent methodological challenges of measurement and interpretation[65,66]. High self-reported life satisfaction is not a guarantee of mental nor emotional health [67] and it is highly influenced by the personal worldviews, beyond life conditions [11,15,65]. Lastly, the most important predictor for life satisfaction are basic needs (*protection* and *subsistence*), despite if social and psychological needs are unfulfilled[16].

Expectation-satisfaction gap

Having satisfied survival needs, QOL depends on how expectations match internal and external capabilities to satisfy needs[11,15,16,65,68]. We assessed expectations as the percentage of population that consider important to satisfy the need of *freedom*, *leisure*, *participation* (democracy) and *creation.* For those needs, the gap between expectation and satisfaction is wider at lower carbon emissions and begins narrowing at increased emissions. However, even at high CF, satisfaction remains below expectations. If expectations rise with increased consumption[3] and the utility of external capabilities is exhausted, people require work on their internal capabilities to feel satisfied[11,18,66].

Thresholds in objective QOL indicators

Objective indicators are more tied to social settings that satisfy population wide needs through infrastructures, medical care and education[16,46]. Indeed, individuals living in societies with functional institutions tend to achieve objective satisfaction regardless of their personal circumstances or subjective satisfaction[16,47]. Moreover, factors such as low fertility rates, urbanization or education levels have proven to have a larger influence on objective measures of well-being once basic needs are covered[2].

Urban safety

The challenges to satisfy the need of protection is more pronounced in urban settings. Sennett argues that urban life often comes with personal insecurity due to the amount of surveillance and the lack of spontaneous and personal social interaction [69]. Specially in stratified societies, a permanent fear of each-other futilely leads to seek safety in private vehicles, insurances or surveilled homes [69].

6. Limitations

Relationships and curve fits

We find robust evidence to confirm or discard relationships between carbon footprints and need satisfaction. However, by using general statistical models to test multiple indicators, we find less evidence (lower R^2) to confirm the definite shape of relationships. Previous studies tailor models in search for the optimal goodness of fit[14,59,61,62,64,70], however this approach grows prohibitive with the amount of indicators[47]. Thus, analyzing multiple indicators may come at the cost of less precise models. Nevertheless, a larger pool of empirical results at the needs level would enable meta-analyses to consolidate findings.

Our results indicate the likelihood of satisfaction given certain carbon footprint of consumption, but do not indicate the effects of specific market goods into quality of life. Although establishing cause-effects between satisfiers and needs is challenging, such knowledge would be crucial to prioritize the most effective satisfiers. Understanding the role of non-consumption factors and social systems could prevent futile resource investments in market satisfiers. Clarifying causal mechanisms would require finer geographical scales and individual level studies to tackle distributional aspects (see "unit of analysis" in SI). Datasets that capture the intended need satisfaction behind consumption while tracking well-being outcomes would enable better scrutiny of the theories (Table 1, SI and main text) than what is possible at national level.

Validity of analysis

Performing a cross-sectional analysis to understand temporal relationships implies the "modernization" assumption. The modernization theory argues that developing nations, subject to economic growth and technological production, tend to follow similar development pathways as wealthy nations [59,71]. This theory is supported by longitudinal studies on societal transitions which confirm such pathways [55,59,62,72,73]. However, drastic changes in technology or policy might invalidate the modernization assumption, as shown by previous studies of nations that achieve high well-being with moderate resources (Goldemberg Corner)[59,70,74]. Thus, as low-carbon energy spreads, land or water become useful complementary indicators of impact [44] In our study based on 2007 data, energy and carbon footprints yield similar results. It is important to note that our analysis is generalizable to middle and high-income nations. Including lower income nations might change some specific results and data availability at the needs level for such nations is a major challenge. Furthermore, there are inherent limitations to cross-cultural analysis based on value and subjective indicators as we discuss in the SI. Given that, our study is based on middle to high income nations, our results cannot be conclusive nor extrapolated to low income nations or to the future. Nevertheless, we encourage the application of this framework to other samples and longitudinal data.

Unit of analysis

Here we look at national level consumption, which is more vulnerable to unequal distribution bias. Unequal distribution is the inherent problem of economic accounting which captures the consumer unit (e.g. government or household) but does not inform about the beneficiaries of the consumption [20]. Functionality refers to the role of physical and cognitive capabilities that mediate the benefit of a commodity [17,18,20,75]. A way to overcome such methodological issues is by refining the geographical unit of analysis as there can be considerable disparity in terms of consumption and life conditions, even within small and wealthy countries [48,76].. Ideally, impact-QOL studies would in parallel look at regional, household and individual data, including measures of internal capabilities. The mismatch between commodities and satisfaction observed in scattered and threshold trends can be attributed to unequal distribution and functionality. Further studies should be replicated at different scales: individual, community, national and global level[46].

Cross-cultural comparability

Despite the common practice and abundant research on cross-country comparisons based on the European Social Survey and World Value Survey, several methodological issues remain. There are inherent issues when comparing subjective or value indicators across countries. The question asked carries the inherent ambiguity of language and therefore subject to the interpretation or so called factor loadings [77,78]. Linguistic differences also induce noise when translating the same question into many different languages[78]. In general, the same term might evoke different meaning for different persons. Like any other subjective human construct, societal values can be whatever people decide they are at a given moment of their lives [78]. For example, income disparities in Peru might be read as hope for socio-economic advancement. While elsewhere, income equality might lead to social frustration[79].

Beyond surveying issues, there are issues when comparing cross-national data by using national values. Namely, within country differences can be significant, especially in ethnographically diverse nations[78]. Values and subjective indicators are most comparable across nation with similar levels of economic and political development[77]. In our database, the less developed nations are Indonesia and India, which are within the middle-income spectrum and half of the sample is towards the middle to high-income spectrum. This means that in our case, comparability is less of an issue as it would be in a bigger sample of nations.
The drawbacks of subjective indicators do not justify their exclusion from sustainability debates. The practical question is whether they provide meaningful information about the status of societies and their transitions[20]. In the quest for trends across societal aspects, the use of these databases seems reasonable. For development research, it certainly makes sense to gather information about individuals' experiences and aggregate them as an indicator of the average human experience in a particular location[20] e.g. If most people are dissatisfied, this will show, regardless if satisfaction has slightly different meaning in the neighboring country.

Scope of indicators

Consumption-based footprints are valuable for informing policies. Territorial footprints[1,71,73] are often poor indicators of the global impact of a nation's consumption[29,35,80]. Built capital and infrastructure drive about 24% of global emissions[35,81] and are excluded from our analysis. While built capital plays a role in QOL, the challenge is to quantify current capital in place and distinguish private from public access infrastructures (see "unit of analysis" in SI) [23]. Further, a drawback is that we only model economic goods, while there are clearly non-economic factors that satisfy needs, [11,15,16] e.g., household production, nature, social systems, free time, etc.

Although choosing indicators is undoubtedly subjective and bound to availability [20], we informed our decisions with literature and frameworks that link indicators to needs [12,24,48,51,52,62,82]. In the previous sections of the SI we justify our choices, discuss their limitations and screen for potentially spurious patterns by testing correlations across indicators. Not surprisingly, we find the strongest correlations between indicators of infrastructure access (electricity, fuels and sanitation), which converge in our results (table 5, main text). Interestingly, we find moderate correlations between objective and subjective satisfaction of *freedom*, *understanding* and *leisure* despite having different trends with respect to their carbon footprints.

7. Supplementary Data File

The supplementary data workbook contains the country-level and rest of the world regions data for the carbon and energy footprints of needs. It includes the satisfaction levels for the 35 quality of life indicators that form the basis of our analysis. We also include the concordance matrix between goods and needs and the full statics from curve fitting. Supplementary economic, demand and population data is also available. This is an overview of the supplementary data file:

1. Total and per capita carbon and energy footprints decomposed by direct and indirect embodied emissions by needs
2. Economic and demographic data. Used to calculate intensities (Figure 3) and elasticities (Table 4)
3. Indicators of need satisfaction derived as described in the Appendix in the SI.
4. Full statistics results of curve fitting tests for energy and carbon. Produced in Matlab 2017
5. Concordance matrix between goods and their associated needs based on the procedure described in the methods and SI.

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Supplementary Information:

PAPER II

Sustainable lifestyle scenarios to curb European environmental impact: *Connecting local visions to global consequences.*

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Sustainable lifestyle scenarios to curb European environmental impact: Connecting local visions to global consequences.

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Contents

From qualitative back casting to quantitative visions

The concrete steps to go from back-casting workshops to a quantitative scenario evaluation are summarized in the figure below.

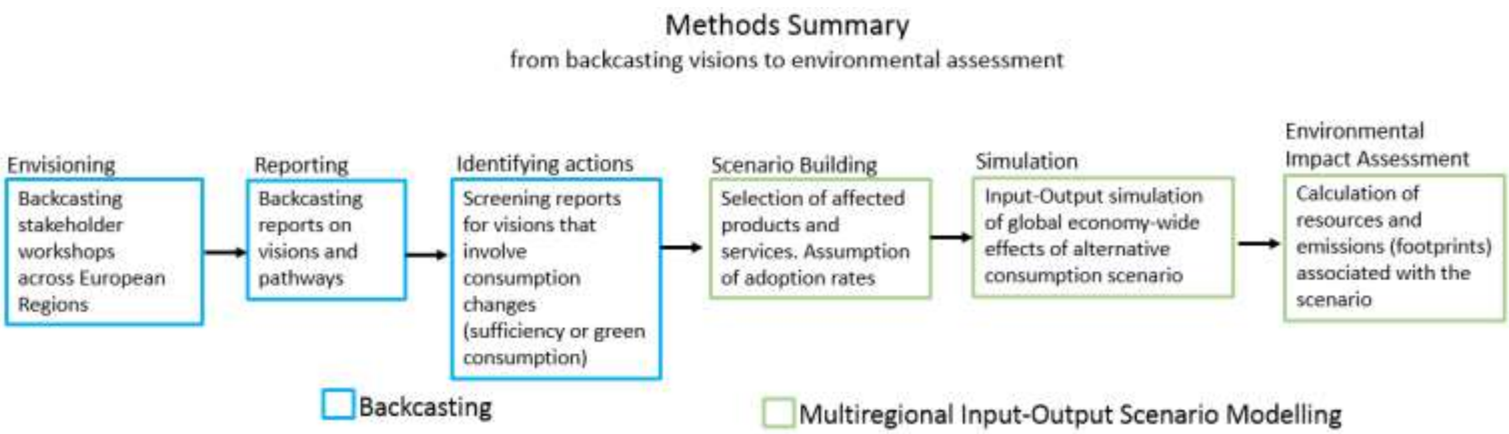


Figure 1 Steps undertaken to translate from qualitative visions to an MRIO framework for environmental impact assessments.

Physical layers for food and energy carriers

Using information on prices per units of mass and coupled with energy content per mass, we calculate the current caloric intake/energy use for all European nations. In green consumption, scenarios, which only imply a product shift, the current energy and caloric consumption (kwh/cap or kcal/cap), were set as a constraint to be respected by the model. In sufficiency scenarios, which imply a net reduction, the constraint is relaxed and the implications for quality of live of such measure are discussed.

The 'housing and 'Food diets' scenarios require a specific modelling methodology which can be summarized in 3 different cases (NB. "energy" will be used indistinctly for both energy in food (kcal/cap) and household energy (electricity and fuels in kWh/cap)):

1. No income rebound but energy as constrain. Food intake or energy remains constant. Household final demand is allowed to vary and can lead to net savings/debt, thus rebound effects are not modelled but the current caloric and energy consumption are ensured(considered in the main text).

2. Energy surplus leading to income rebound. Energy is kept as a constrain like above. Household final demand is allowed to vary but when the modelled lifestyle leads to savings the surplus money is re-spent (rebounded) in the same proportion as current expenditure in all other products (considered in the rebound section in the SI).

3. Energy deficit leading to demand withdrawn from other products. Same adjustment as above, but when the interventions leads to an energetic deficit, it means that money has to be "taken" from other products to satisfy the modelled lifestyle demand in terms of energy. This could happen for example for the 'Careless Consumer' where expensive ready-made and processed food which has less caloric content and thus requires more money to keep calories constant.

For each of the food products, the calorific output (in kilocalories) per monetary unit (million Euros) was calculated as

$$Calorific\ output\ \left[\frac{kcal}{MEuro}\right] = Calorie\ content\ \left[\frac{kcal}{ton}\right] *\ Price^{-1}\ \left[\frac{ton}{MEuro}\right]$$

Information on the calorie content in each food product was taken from the National Nutrient Database of the United States Department of Agriculture[1]. Supplementary data was taken from the Finnish National Food Composition Database [2]. The values, equivalences and assumptions for energy carriers and foods are available in the supplementary dataset. We made assumptions to approximate how much of the weight of each raw product, for example pigs, is eligible to be consumed as calories (since prices underlying EXIOBASE are weight-based[3]). This is the "edible ratio" in the Supplementary Data. Estimated calorific intake share calculated from household final demand was compared to data from the Food and Agriculture Organization of the United Nations[4], presented as FAO share in the Supplementary Data File.

For the *Less Waste* food lifestyle, it was necessary to estimate the amount of food wasted by EU households. The avoidable consumer food waste was in 2015 estimated to be 12% of the food reaching consumers, based on weight units[5]. We assume the same value for the year 2007 and that the mass reductions in waste roughly reflect the demand reduction[6]. A 12% reduction of food-product spending was therefore applied proportionally across food products for this scenario. For the *Eat Less* food lifestyle it was assumed that dietary intake is equal to that of the EU country with the lowest calorific intake; namely the Republic of Moldova with 2586 kcal/cap/day[4]. This is within the range of calorie need for a moderately active male[7] and in agreement with previous modelling of sufficient intake[8]. The average dietary intake in EU is 3370 kcal/cap/day. Calorie reduction was thus assumed as:

$$Reduction\ of\ Demand = 1 - \frac{Minimum\ Calorific\ Intake}{Actual\ Calorific\ Intake} = 1 - \frac{2586}{3370} = 0.233$$

In our model, a calorie reduction of 23.3% corresponds approximately to a household final demand reduction of 27%. Household technical potential for *Eat Less* was therefore set to 0.27. Eat Less does not include calorie reduction from hotel and restaurant spending. Therefore, because some of the actual calorie supply is coming from the hotel and restaurants, the calorie reduction of Eat Less was lower than the total final demand reduction. A maximum reduction potential for food lifestyles was calculated by combining the lifestyles of vegan diet, organic food, no food waste, and reduced calorific intake. The sum of the reduction potential of each of these lifestyles was compared to the total EU household impact in 2007.

Previous food research based on EXIOBASE has equated food consumption to food intake while acknowledging the bias on doing so: "Although these data include wastes from processing, packaging, and transport, they do not include consumer waste and so do not correspond to the average consumed diet." (p. 13415,[9]). In this research we try to approximate purchase to actual intake by assuming edible ratios out of the mass units of each food product. The supplementary data files contain the estimated calorie content of the EXIOBASE food products[1,2]. Each EXIOBASE product is compared to its equivalent product based on the specifications stipulated under the International Standard Industrial Classification of All Economic Activities ISIC classification definitions[10] from the sources of the calorie information[2,11]. Edible ratios, calorific intake as share of household calories and the comparison to FAO shares, and the sources for assumptions are available in the supplementary data file.

For the energy products, we used prices of on energy content (TJ) per monetary unit for the different energy carriers underlying EXIOBASE[3] and coupled with information on energy per mass unit by the International Energy Agency[12]. For household fuels such as coal, gas, and liquid petroleum, lower heating value (net calorific value) were obtained from[12]. Energy content for peat was obtained from[13]. Unlike electricity, the energy content of household fuels does not directly correspond to the usable heat that is possible to extract. Thus a direct conversion from monetary intensity per TJ to total energy delivered is not possible for solid and liquid fuels. Each fuel product therefore required the assumption of a heating efficiency equal to one of four types of the average efficiency of a home-heating system[14–17]. By multiplying the heating efficiency with the lower heating value, the useful energy (TJ/ton) of each fuel was estimated. See supplementary data for the estimated values. From the average European basic prices per mass of fuels, the energy price was obtained as

$$Energy\ price_{household\ fuel}\ \left[\frac{MEuro}{TJ}\right] = \frac{Weight\ price\left[\frac{MEuro}{ton}\right]}{HE * LHV[\frac{TJ}{ton}]}$$

where HE is the heating efficiency and LHV the lower heating value for a specific fuel.

The supplementary data file contains the estimation of useful energy in household fuels. NCV (Net Calorific Value or Lower Heating Value) measures the amount of energy released in combustion of specific fuel. Due to the disparity of household technologies for combustion of solid and liquid fuels within Europe, the least effective heating system (HS) for each fuel is assumed, namely 1) non-catalytic wood stove Pacific Energy fireplace[14], 2) non-condensing furnace[15], 3) steam furnace for fuel oil[17], and 4) Stockton 14HB high output boiler stoves[16]. The lower efficiency value was chosen as a conservative measure as it was typically closer to the average efficiency among devices. Assuming higher efficiencies would imply that most heating systems for solid and liquid fuels in the European Economic Area latest technologies, whereas as these fuels are mainly used in low-income countries and households. Heating Efficiency (HE) determines the efficiency of the heating system. Useful Energy is obtained from the NCV and HE of each fuel (see supplementary data file).

For the Passive House, we assumed that it is possible to reduce energy consumption by 40%. This was based on 1) comparing theoretical maximum reduction potential by comparing current average space heating needs[18] to a passive house standard (15 kWh/m^{2}yr)[19], 2) a study of maximum achievable potential of energy efficiency measures in the U.S[20], 3) Assuming that people live in the most efficient type of buildings (flats, apartment buildings, etc.)[21]. In our model, a 40% energy consumption reduction corresponds to reducing final demand by 43%. Because a share of the total final demand reduction is for product distribution services of gaseous fuels which does not have energy use associated with it, a higher final demand reduction was required than the 40% energy consumption reduction.

Assumptions for uptake rates

Assumptions for uptake rates in food and housing scenarios that require an energy balance are done according to the model constraint and literature, as explained above. An overview of the type of fuels and food products affected in each scenario are described in the Table 3 in the main text and in more detail under the "Modelling parameters" tab in the Supplementary Data file.

The assumptions for the uptake rate in the sensitivity scenarios are made heuristically by the authors by either following the same uptake rate of the lifestyle vision or stating a reasonable rate based on expenditure and price data e.g., only 2% of all other expenditure goes into *Frequent Flying* because more than that might yield an unrealistic amount of sky miles considering that we model household consumption and thus private/leisure travel. The rest of the cases come from the normative statements by "experts", "stakeholders" and "researchers" indicating which adoption rate is achievable and desirable in their view. We try to respect such statement as much as possible but do interfere in some cases where the statement might be unrealistic e.g., food waste can be reduced significantly but not totally eliminated.

All the assumptions of uptake rates related to transport reductions come from the GLAMURS quantitative survey results of work related travel[22] and other time-use studies[23] (see other papers in this special issue). The assumptions in the categories of Services, food sourcing and clothing come from the sustainability front-runners and citizens who participated in the workshops (see supplementary data file).

A limitation of modelling household demand through MRIO is the omission of infrastructure capital. For example, overlooking the infrastructure required to deploy renewable electricity leads to overoptimistic results. Nevertheless, large scale analysis that accounts for capital infrastructures of specific technologies report similar potential (carbon reductions) and trade-offs (increases in water and land) from shifting to renewables[24,25]. Similarly, neglecting transport infrastructures provided by government such as roads, parking, railways, tunnels, stations etc. might discount impacts from transport with high infrastructure requirements but lower operating emissions, such as trains[26].

Geographical coverage

Nations and world regions modelled in the analysis (RoW: Rest of World)[27]	
European Economic Area	***Foreign***
Austria	*USA*
Belgium	*Japan*
Bulgaria	*China*
Cyprus	*Canada*
Czech Republic	*South Korea*
Germany	*Brazil*
Denmark	*India*
Estonia	*Mexico*
Spain	*Russia*
Finland	*Australia*
France	*Turkey*
Greece	*Taiwan*
Hungary	*Indonesia*
Ireland	*South Africa*
Italy	*RoW Asia and Pacific*
Lithuania	*RoW America*
Luxembourg	*RoW Africa*
Latvia	*RoW Middle East*
Malta	
Netherlands	
Poland	
Portugal	
Romania	
Sweden	
Slovenia	
Slovakia	
UK	
Switzerland	
Norway	
RoW Europe	

Sensitivity analysis: Results considering economic rebound effects from savings (keeping current total expenditure constant)

The potential of adopting sustainable lifestyles changes that bring about economic savings are often conditioned to the extent of the rebound-effect. However, since the lifestyle scenarios proposed by stakeholders are driven by environmental motivations, we do not expect the economic rebound to take place as in cases where the behavioral change is driven by economic motives[28], specially for sufficiency lifestyles. Nevertheless, we model the possible outcomes of a rebound-effect to characterize the uncertainty of our scenarios.

The technical rebound effect that comes with efficiency increases has been consistently found in empirical studies [29–32]. The economic-rebound effect, on the other hand, occurs when a certain environmentally oriented behavioral change brings about savings and those savings are spent on equally or more harmful consumption that undermines the environmental benefits. We account for this possibility by modelling the income rebound effects.

Modelling income rebound effect

In cases where lifestyle changes lead to monetary savings, depending on how these savings are spent, the scenario can lead to worse environmental outcomes (see figures below). A lower cost of the alternative lifestyle will result in money being available for re-spending. The savings are distributed proportionately across all the products not affected by the scenario. Since final demand of new products cannot be larger than the substituted final demand, the maximum (and default) value for price difference is 1. Thus the model does therefore not take into consideration situations where the lifestyle scenario is more expensive than the baseline (Except for dietary changes where is more costly to supply same calories, see physical layer section above). Naturally, scenarios that imply full product substitution without any price differences yield no savings and thus no difference in results that consider rebound (see figures below). Finally, only scenarios dealing with household savings are affected by the rebound effect. Dynamics of behavioral response or macro-economic price propagation are disregarded, assumed that industrial sectors, as opposed to consumers, generally either try to make a profit out of the savings, or are compelled to pass on savings to consumers.

In our model, the economic rebound effect is modelled by proportionally distributing the savings to increased consumption of all products from all countries unaffected by the scenario. The new consumption due to rebound $\mathbf{y}^{\text{reb}}$ is given by:

$$y_{\text{o}}^{\text{reb}} = \left(\sum \mathbf{y} \; - \sum (\mathbf{y}^{\text{red}} + \mathbf{y}^{\text{sub}})\right) * \frac{y_{\text{o}}}{\sum_{\text{g}} \mathbf{y}} \qquad \forall(\mathbf{o} \notin \mathbf{i} \cup \mathbf{g})$$

$$y_{\text{o}}^{\text{reb}} = 0 \qquad \forall(\mathbf{o} \in \mathbf{i} \cup \mathbf{g})$$

Note that a specific rebound (e.g. if newly available money is supposed to be spent on specific products) can be modelled with the substitution mechanism described in Equation 2 (main text).

The new total final demand vector $\mathbf{y}^{\text{tot}}$ is then given by:

$$\mathbf{y}^{\text{tot}} = \mathbf{y}^{\text{red}} + \mathbf{y}^{\text{sub}} + \mathbf{y}^{\text{reb}}$$

Rebound Results

Housing

With rebound there would be no significant decrease of land or toxicity footprints and a net increase of water footprint in housing scenarios. Carbon reduction potential would still be significant (9.53%). Housing is the most carbon intense consumption category of all but only moderate in terms of land, water, and toxicity footprint multiplier (Table 2, main text).

The technical rebound effect for residential end-uses has a wide range of 7-50%[33–36]. Although here we model income-rebound, this implies that at sufficiency and efficiency lifestyles could have a wide range of outcomes, depending on how the rebound is managed. In conclusion, the mitigation potential of most housing scenarios that imply substitution with current energy demand present a slight risk of trade-offs across footprint categories, if rebound is considered.

Transport

We generally find large trade-offs in the transport scenarios when considering rebound. All transport sufficiency scenarios show large potential increases in land and water footprints, ranging from 4.22% (Flex Work Half) to 8.44% (Bike Walk Full) for land footprint when considering the rebound effect. Transport is relatively lower in land and water intensity as compared to other products (Table 2, main text), underlining the importance of considering the potential damage from spending the savings of reduced transport.

Our sensitivity check assumes a full income-rebound effect. However, literature estimated the rebound effect to be around 30% for mobility interventions [36,37] in which case there would moderate increases of land and water footprints but still a significant reduction of carbon footprints.

Services

The low emission intensity of service products means that if all the final demand is rebound towards non-service products the environmental footprints for EU households will drastically increase. All footprints would increase from around 40-50% if full rebound occurs.

Construction

All lifestyles except *Minimum Renovation* are based on full substitution of final demand of construction materials and construction services, therefore there would not be a rebound effect. Consideration the rebound effect of saving money from renovating less, the water footprint would increase, indicating that construction products use relatively less water

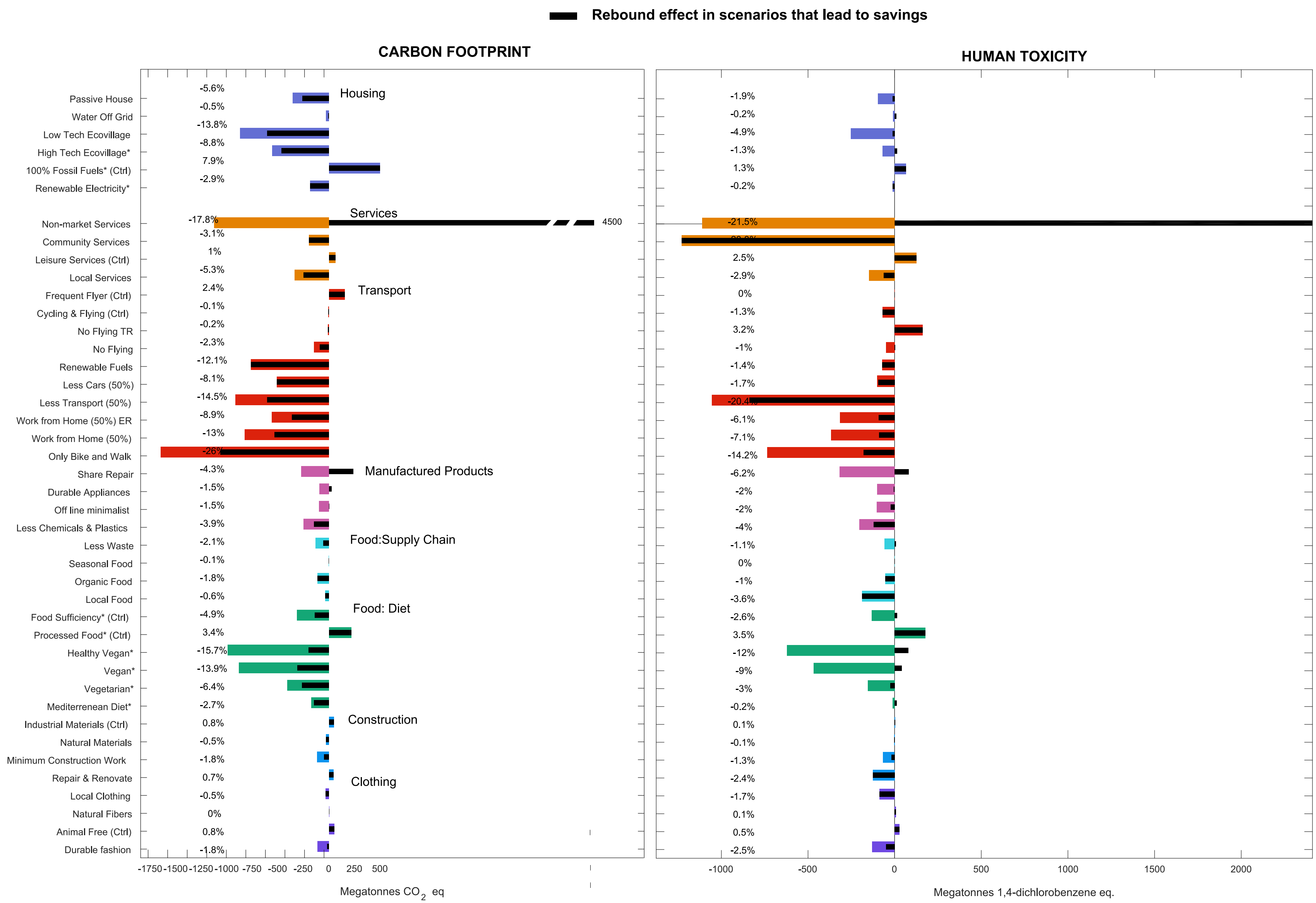
Food

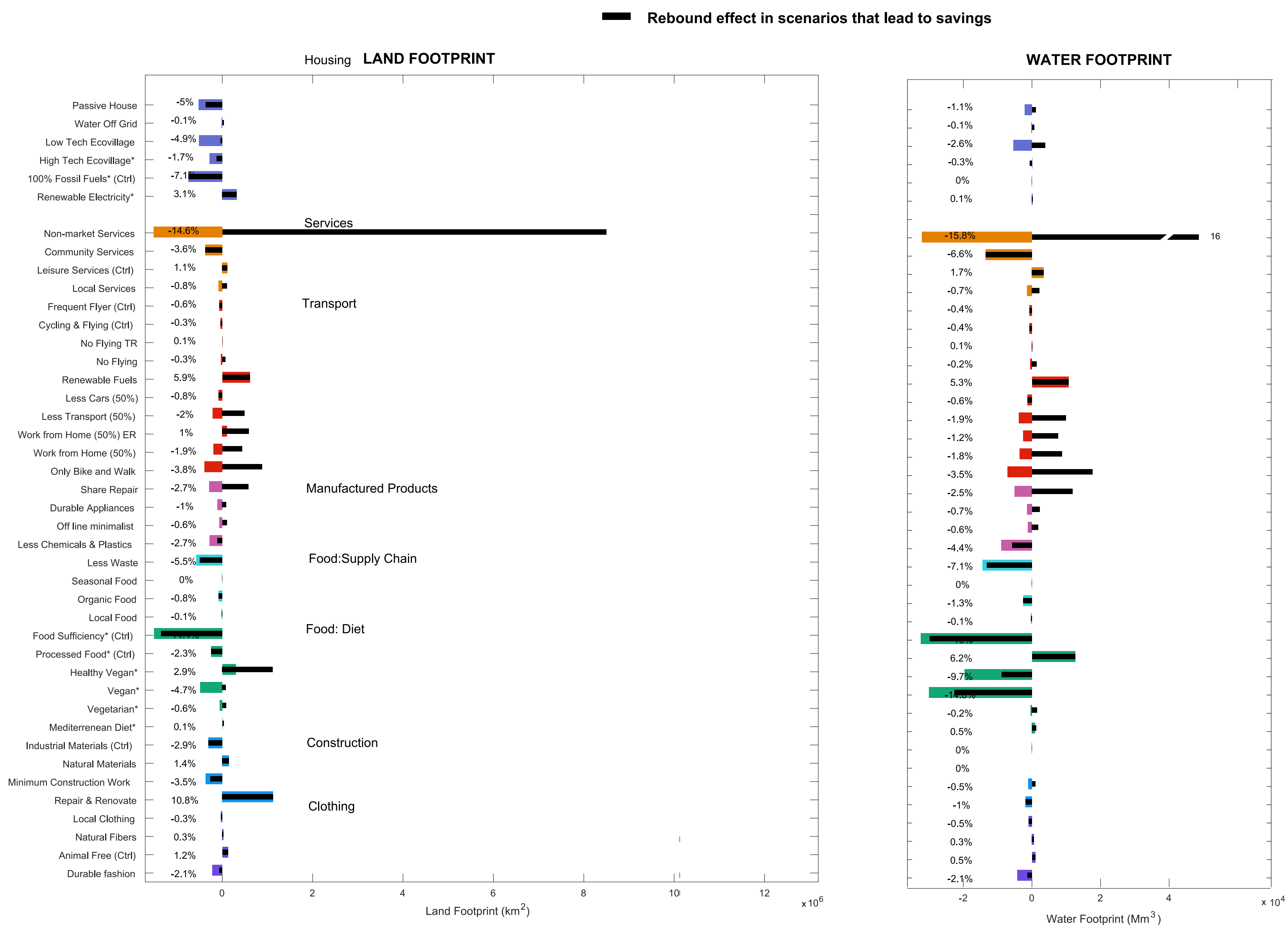
To maintain a constant calorie intake with the scenario, consuming vegan products only requires less household spending on food. When the savings of shifting diets are reallocated to other products, there is a marked rebound for all low-meat lifestyles, because staples, fruits and vegetables are usually less processed and cheaper than meat products. Our estimation of plant based diets being less costly is confirmed by household level empirical findings on vegetarianism in Europe[38,39].

The vegan diet scenario involves substantial savings which could potentially be re-spent within other consumption categories. The income-rebound for the vegan lifestyle would offset roughly 65% of the food-related GHG reductions. It has been shown that rebound within food spending could offset up to 50% of expected GHG reductions[34], slightly lower than our approximations. On the other hand research suggest that in Spain, shifting toward a vegetable-based (and healthier) diet may yield a net increase of GHG emissions due to the rebound effect[40]. Our results do not point in the same direction. With rebound, the vegan still has the highest reduction potential and could decrease carbon and water footprints by 4.89 and 11.17%, respectively.

Manufactured products

Even if the money saved from reducing manufactured products is re-spent, there are still a significant mitigation potential in using *Less Chemicals*. The rebound effect may offset any potential benefit of the *Durable Appliances*, *Off-line minimalist*, or *Share Repair*. Especially in terms of land and water footprint, the rebound effect causes increases of footprint for these scenarios. This is explained by the lower-land and water- intensity of manufactured products (Table 3, main text)


Rebound effect in scenarios that lead to savings
CARBON FOOTPRINT
HUMAN TOXICITY
Housing
Passive House
Water Off Grid
Low Tech Ecovillage
High Tech Ecovillage*
100% Fossil Fuels* (Ctrl)
Renewable Electricity*
Services
Non-market Services
Community Services
Leisure Services (Ctrl)
Local Services
Transport
Frequent Flyer (Ctrl)
Cycling & Flying (Ctrl)
No Flying TR
No Flying
Renewable Fuels
Less Cars (50%)
Less Transport (50%)
Work from Home (50%) ER
Work from Home (50%)
Only Bike and Walk
Manufactured Products
Share Repair
Durable Appliances
Off line minimalist
Less Chemicals & Plastics
Food:Supply Chain
Less Waste
Seasonal Food
Organic Food
Local Food
Food: Diet
Food Sufficiency* (Ctrl)
Processed Food* (Ctrl)
Healthy Vegan*
Vegan*
Vegetarian*
Mediterrenean Diet*
Construction
Industrial Materials (Ctrl)
Natural Materials
Minimum Construction Work
Repair & Renovate
Clothing
Local Clothing
Natural Fibers
Animal Free (Ctrl)
Durable fashion
4500
Megatonnes CO2 eq
Megatonnes 1,4-dichlorobenzene eq.



Rebound effect in scenarios that lead to savings
LAND FOOTPRINT
WATER FOOTPRINT
Housing
Services
Transport
Manufactured Products
Food:Supply Chain
Food: Diet
Construction
Clothing
Passive House
Water Off Grid
Low Tech Ecovillage
High Tech Ecovillage*
100% Fossil Fuels* (Ctrl)
Renewable Electricity*
Non-market Services
Community Services
Leisure Services (Ctrl)
Local Services
Frequent Flyer (Ctrl)
Cycling & Flying (Ctrl)
No Flying TR
No Flying
Renewable Fuels
Less Cars (50%)
Less Transport (50%)
Work from Home (50%) ER
Work from Home (50%)
Only Bike and Walk
Share Repair
Durable Appliances
Off line minimalist
Less Chemicals & Plastics
Less Waste
Seasonal Food
Organic Food
Local Food
Food Sufficiency* (Ctrl)
Processed Food* (Ctrl)
Healthy Vegan*
Vegan*
Vegetarian*
Mediterrenean Diet*
Industrial Materials (Ctrl)
Natural Materials
Minimum Construction Work
Repair & Renovate
Local Clothing
Natural Fibers
Animal Free (Ctrl)
Durable fashion
Land Footprint (km²)
x 10⁶
Water Footprint (Mm³)
x 10⁴
16

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Supplementary Information

PAPER III

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

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

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Contents

Sampling

In this section we provide information about the grassroots initiatives and the geographical regions in which they operate. In addition to the initiative sample sizes, we reported population sizes, or the number of active members in each organization given availability. It should be noted, however, that these numbers are rather estimative (even though they were reported directly from initiatives). This is due to the fluid nature of the initiatives and the notable degree of the membership turnover and fluctuations. In this section, we use N_p refer to the entire population of initiatives and regions.

Initiatives in Galicia (ES)

The initiative sample from Galicia included a total of 59 initiative members. The general focus of the grassroots initiatives was on consumption of food and consumption of manufactured goods. The calculation of the members is done by family unit, where each family has one email address.

- *Zocamiñoca,* a food consumption cooperative belonging to the Galician Network of Conscious and Responsible Consumption; engaging local retailers and focusing on local consumption (n=40, N_p ~150)
- *Amarante Setem*, promoting sustainable fashion and textile production; reduced consumption of textiles, fair trade and responsible consumption (n=13, N_p ~15)
- *Equus Zebra*, a non-governmental association providing integration and support for African immigrants in Galicia by selling second-hand clothing (n=6, N_p ~16)

Initiatives in Banat-Timis county (RO)

Grassroots initiatives in this region included eco villages, living an exemplary sustainable life. Their extensive approach covered new lifestyle choices, consumption habits and time-use patterns. They were built on the principles of permaculture, downshifting and a sharing economy. The initiative sample from Banat-Timis included a total of 20 members.

- *Aurora*, practice of permaculture, downshifting, deep ecology and various community building approaches (n=3, N_p ~5-10)
- *Amonia Brassovia* (n=17, N_p ~80)

Initiatives in Lazio (IT)

The initiative sample from Lazio included a total of 27 initiative members. Several initiatives of a network of agricultural cooperatives were contacted, all of which share a focus on sustainable food production and consumption, local and organic agriculture, and common land cultivation. The *CoRAgGio* Cooperative was the main target initiative and at the time of the survey it had 17 members. Other participants are formally members of other initiatives, part of the same network as *CoRAgGio*, sharing agendas and cooperating in their activities.

- *CoRAgGio* (n=14, N_p ~17)
- *CoBrAgOr* (n=1)
- *Associazione Parco AgricoloCasal del Marmo* (n=8)
- *Terra!* (n=2)
- *daSudv* (n=2)

Initiatives in Saxony-Anhalt (DE)

The initiative sample from Saxony-Anhalt included a total of 35 initiative members. The selected grassroots initiatives were concerned with local food production, food sharing, a local currency and community-supported agriculture.

- Members of the *Transition Town Halle*, social movement raising awareness of sustainability; local food production; do-it-yourself; (n=21, N_p ~30)
- *Lebensmittel retten Magdeburg* (n=14, N_p ~40)

Non-members

The sample of non-members consisted of adult population (over 18) of both genders, residing in the respective regions where initiatives operate. The sampling size was computed based on the population of the respective region:

$$n = \frac{N_p \sigma^2 Z^2}{(N_p - 1)e^2 + \sigma^2 Z^2}$$

Where n referred to the sample size, N_p to the population size, σ to the standard deviation of the population (when the value is unknown a constant value of 0.5 is used), Z to the value obtained with confidence levels (1.96 for 95% confidence interval), and e to the accepted limit of sampling error (when this value is not known, a value between 1% (0.01) and 9% (0.09) is used). Based on the sample size formula and a sampling error of 5%, we calculated the effective size of the non-member samples to be 384 individuals across all countries. SI Table 1 contains actual samples of the non-members included in our study.

Region	Country	Population[1] (N_p)	Actual control groups sample
Galicia	ES	2,734,656 (Galicia, NUTS2)	n= 429
Banat-Timis	RO	695,599 (Timiş County, NUTS3)	n= 272
Lazio	IT	5,892,425 (Lazio, NUTS2)	n= 431
Saxony-Anhalt	DE	2,235,548 (Saxony-Anhalt, NUTS1)	n= 344

SI Table 1: Non-members sample and population sizes. Effective size for all regions is 384 individuals.

Surveying procedure

The final survey was programmed as an online questionnaire in English. It contained questions on lifestyle domains, socio-demographics, economic status, footprint-relevant behaviors and psychological constructs (e.g. norms, values, aspirations). Project researchers from every country translated the items into the local languages. Translation was made through a back-translation process to ensure that the items conveyed equivalent meaning across languages. A thorough online survey was prepared and coded employing the SoSci software. A pilot survey was conducted in two of the regions – Galicia (ES) and Saxony-Anhalt (DE) – to test the comprehension of the survey and the validity of measures. The pilot samples included 94 and 50 respondents, respectively. The final survey was adapted based on the insights from the pilot.

The link to the final survey was distributed between the months of December 2015 and February 2016, e.g., using mailing lists or contracting a company ensuring a representative sample from the region. The samples were recruited in a multi-stage process with a phase of contacting participants via a snowball-system adopted across all case studies. Data was collected as a single dataset to enable direct inter-regional comparisons. Detailed official statistics and discussion on representativeness have been provided by Dumitru and colleagues (2016)[2].

Membership was established through key informers, with each initiative having their own criteria for defining membership. The survey was sent to members referred to by key informers, which normally held a leadership role in the organization.

Carbon footprint calculator

Food

Bottom-up physical calculations based on diets and intake

The final survey collected data on consumption frequencies of meat, dairy products, vegetables and fruits, and beverages, which we used to calculate bottom-up the carbon footprint of these items. 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[3]. SI Table 2 reports product-level daily consumption by country in grams per kilogram of body weight.

The average daily consumption was used in combination with respondents' weight and weekly frequency of consumption to calculate adequate daily intake across food items. In addition, lifecycle assessment (LCA) studies were used to inform the carbon intensities of food items, with results standardized in kgCO_2eq/kg edible product. The following carbon intensities were applied (in kgCO_2eq/kg of edible product): beef (27.87), pork (7.36), chicken (5.44), dairy products (4.07), vegetables and fruits (0.70).

Finally, we assigned the footprint of "Other meat products" to respondents based on meat consumption frequency from the survey, country-specific daily intake (incl. edible offal, sausages, meat specialties and imitates)[3] and EXIOBASE 2.3's price and footprint accounts (11% of EU's food footprint)[4].

Country	**Spain (ES)**	**Romania (RO)**	**Italy (IT)**	**Germany (DE)**
Beef	1.03	0.34	0.63	0.70
Pork	0.82	0.69	0.54	0.74
Chicken	1.02	0.91	0.73	0.91
Other meat products	0.42	0.65	0.44	0.71
Dairy products	5.80	2.09	2.80	2.67
Vegetables and fruits	9.16	9.45	8.38	11.47

SI Table 2: Average daily consumption in gr/kg of body weight.

Gap food items based on expenditure and top-down assessments

In addition, data on food expenditure was collected and coupled with regionalized carbon intensities[4] (SI Table 3) to account for the footprint of "other food" items (e.g., processed food, fish products, crops not else classified, etc.). In particular, we adopted the regional consumption structure and varied the consumption level based on the reported store-bought food. We excluded the food products that the survey covered directly to avoid double-counting. Footprint calculations of non-members were validated with prior product-level assessments of region-specific carbon footprints[4].

Region	**Galicia (ES)**	**Banat-Timis (RO)**	**Lazio (IT)**	**Saxony-Anhalt (DE)**
Processed food	1.28	0.86	0.68	0.74
Other food consumption	0.55	1.28	0.17	0.41
Clothing	0.32	0.65	0.49	0.60

SI Table 3: Carbon footprint intensities from EXIOBASE2 in kgCO_2eq/EUR of consumption (basic prices).

Clothing

We utilized carbon monetary intensities from the regionalized EXIOBASE2 analysis to produce clothing-based footprints[4] (SI Table 3). Furthermore, respondents have been asked about their share of second-hand clothing purchases which was then discounted, thus, assigning impacts only to the purchase of store bought clothes.

Housing

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[5]. The climate impact of electricity was calculated using country-level carbon intensities from Eco-Invent 2.2[6] (SI Table 6). We discounted any space and water heating delivered by electricity to avoid double-counting.

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 was modelled using the Intelligent Energy Europe project TABULA[7]. It was primarily designed to collect and compare data of example buildings representative of the national building stock in Europe. The calculation of space heating is based on estimating the typical energy demand (in kWh/m²) given the (1) type of house, (2) year of construction, (3) the level of refurbishment and the (4) climate zone of the region ($R^2 = 0.48$). Regression coefficients were estimated based on the pooled European sample for the 4 types of dwelling, 6 construction periods, 3 levels of refurbishment and 8 climate zones (SI Table 4).

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

Variable	Unstandardized Coefficients	Std. Error	Standardized Coefficients	t	Sig.
(Constant)	319.021	9.559		33.374	.000
Climate Zone	-6.901	1.117	-.121	-6.180	.000
Construction Period	-14.560	.864	-.328	-16.853	.000
Refurbishment level	-45.416	1.631	-.541	-27.840	.000
Terraced House	-25.391	3.691	-.152	-6.879	.000
Multi-Family House	-29.804	3.549	-.187	-8.398	.000
Apartment Building	-42.125	3.781	-.244	-11.140	.000
Adjusted R^2	0.470				
Obs	1412				

SI Table 4: Regression analysis on dwelling sample from TABULA with dependent variable annual space heating demand.

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. Data on preferred indoor temperatures were collected but were not considered for the space heating calculation, which assumed a default 20°C indoor temperature. The hot water demand was calculated using a model in function of occupants[8].

Carbon intensity of energy carriers for space and water heating was based on the Tabula[7] (SI Table 6). We validated our estimated heat demand and shares of fuels with Eurostat's statistics for the residential sector in the studied nations[9]. We excluded emissions embodied in construction materials, quantified to account for about 20% of lifecycle GHG emissions for average European buildings[10].

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. The following carbon intensities in $kgCO_2eq$/km-passenger 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, we used combustion and life cycle emissions as follows: petrol (2.957 $kgCO_2eq/L$), diesel (3.108 $kgCO_2eq/L$), hybrid petrol (2.957 $kgCO_2eq/L$), LPG (2.361 $kgCO_2eq/L$). Region-specific carbon emission factors were adopted with regards to electricity consumption ($kgCO_2eq/kWh$). Car production emissions data was measured in $kgCO_2eq/km$, reported by type of car motor: petrol (0.062), diesel (0.057), gas (0.062), electricity (0.051) and hybrid (0.048). See SI Table 6 for all emission factors being used and Table 5 for car's fuel consumption efficiencies.

Type of car	**City car**	**Compact**	**Family car**	**Large car**
Petrol	0.058	0.058	0.074	0.099
Diesel	0.048	0.048	0.058	0.082
Hybrid (petrol-electric)	0.029	0.029	0.041	0.058
Electric car	0.125	0.125	0.147	0.188
LPG	0.095	0.095	0.131	0.136

SI Table 5: Fuel efficiencies by type of car and fuel measured in L/km or kWh/km for electric cars.

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[11] (SI Table 6).

The lifecycle analysis literature review, sources and statistical analysis behind the transport emission factors and fuel efficiencies are available in a supplementary data file.

Summary of environmental intensities

Product	LCA/MRIO method	Unit	Intensity used	Remarks	Sources	Consumption variables used
Beef	LCA	$kgCO_2eq/kg$ edible product	27.87	16.43[12] (Min), 22.14 (Q1), 31.45 (Q3), 41.00[13] (Max)	[3,12–18]	FC3a
Pork	LCA	$kgCO_2eq/kg$ edible product	7.36	2.96[19] (Min), 4.80 (Q1), 9.07 (Q3), 13.55[20] (Max)	[3,13,14,17,19–26]	FC3b
Chicken	LCA	$kgCO_2eq/kg$ edible product	5.44	2.71[13] (Min), 3.58 (Q1), 6.73 (Q3), 9.54[14] (Max)	[3,13,14,17,20,27–33]	FC3c
Dairy products	LCA	$kgCO_2eq/kg$ edible product	4.07 (aggregated based on the country % consumption of milk, cheese and yoghurt[3])	Milk: 0.78[19] (Min), 1.50[34] (Max); Cheese: 7.49[35] (Min), 10.44[36] (Max); Yoghurt: 1.776[37] Estimated IRQ range: 3.73 (Q1), 4.39 (Q3) (aggregated based on the country % consumption of milk, cheese and yoghurt[3])	[3,13–15,18–20,34–46]	FC3d
Vegetables and fruits	LCA	$kgCO_2eq/kg$ edible product	0.70 (aggregated based on the country % consumption of vegetables and vegetable products, starchy roots and tubers, and fruits and fruits products[3])	Vegetables and vegetable products: 0.08[17] (Min), 9.40[14] (Max); Starchy roots and tubers: 0.09[17] (Min), 0.35[17] (Max); Fruits and fruit products: 0.04[47] (Min), 0.85[48] (Max) Estimated IRQ range: 0.13 (Q1), 1.06 (Q3) (aggregated based on the country % consumption of vegetables and vegetable products, starchy roots and tubers, and fruits and fruits products[3])	[3,14,17,21,29,47–59]	FC3f
Processed food	MRIO	$kgCO_2eq/EUR$	1.28 (Galicia, ES), 0.86 (Banat-Timis, RO), 0.68 (Lazio, IT), 0.74 (Saxony-Anhalt, DE)		[4]	FC2a, FC3e
Other food	MRIO	$kgCO_2eq/EUR$	0.554 (Galicia, ES), 1.279 (Banat-Timis, RO), 0.166 (Lazio, IT), 0.407 (Saxony-Anhalt, DE)		[4]	FC2a, FC3g
Clothing	MRIO	$kgCO_2eq/EUR$	0.323 (Galicia, ES), 0.648 (Banat-Timis, RO), 0.491 (Lazio, IT), 0.597 (Saxony-Anhalt DE)		[4]	SB1, SB2c
Electricity	LCA	kgCO2eq/kWh	0.5184 (Galicia, ES), 0.7452 (Banat-Timis, RO), 0.6569 (Lazio, IT), 0.6586 (Saxony-Anhalt DE)	National Electricity mix	Eco invent 2.2[6].	EU6a, EU6b, EU8
Space and water heating	LCA	$kgCO_2eq/kWh$	From primary to delivered energy. 0.33 (Oil), 0.277 (Gas), 0.04 (Wood Pellets), 0.001 (Solar Thermal Heater), 0.038 (Electric/gas heat pump), 0.42 (District Heating)	European average to prevent noise from country-specific factors.	Emission factors for oil, gas, and wood pellets. Are used according to EN 15603 Annex E)[60] . values for solar thermal heating, district heating and heat pumps[6]	EU1a, EU2, EU3, EU7, EU11, SD5
Non-car land travel	LCA	$kgCO_2eq/km$	Production and end of life emissions: 0 (Walking), 0.005(Cycling), 0.018 (e-Cycling), 0.120 (Motorbike), 0.198 (Generic Car), 0.132 (Diesel Bus), 0.015 (Tram/metro), 0.019	Direct emissions considered in the factor for motorbike. National electricity mix used to power rail transports.	See supplementary data file for sources.	MB1, MB2

			(regional train), 0.304 (plane).			
Car travel	LCA	$kgCO_2eq/L$ and $kgCO_2eq/kWh$	Fuel Production: 0.572 (Petrol),0.468 (Diesel), 0.572 (Hybrid petro-electric), National electricity mix (Electric), 0.868 (LPG). Direct combustion: 2.384 (Petrol), 2.640 (Diesel) 2.384 (Hybrid petro-electric), 0 (Electric), 1.493 (LPG)	European average to prevent noise from country-specific factors (except electricity). Fuel efficiencies according to car type and size in Table 4.	See supplementary data file for sources	MB3, MB4a, MB4b, MB4c, MB4d, MB6a, MB6b
Air travel	LCA	$kgCO_2eq/km$	0.305 (Short flights), 0. 25057 (long flights).	Short haul assumption:3500 km, Long haul: 8000 km	[11]	MB8, MB9a, MB9b

SI Table 6: Summary of environmental intensities and consumption. In the case of Life Cycle Assessment (LCA) intensities, an average is used where not explicitly mentioned. Figure 2 combines "Processed food" and "Other food" in a single category. All of them converted using the GWP100 metric (IPCC 2007, see attached data file). LCA: Life Cycle Assessment. MRIO= Multiregional Input-Output

Validation and uncertainty

We compared the carbon footprint distribution of the non-member sample with prior impact assessment of 177 regions in 27 EU countries[4] (SI Table 7). The prior 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. Both studies offer the same geographical coverage (NUTS level[61]) for Galicia (ES) and Lazio (IT), and Saxony-Anhalt (DE). There was a slight difference for the Romanian case which covers the Banat-Timis region (Timiș county) in our study, which lies within the larger NUTS2 "West Romania" region.

The difference between the food totals varied with less than a ton of CO_2 equivalents per capita (tCO_2eq/cap) across all geographical areas, where we found 6-40% higher food footprints. Our food estimates were largely driven by other food consumption on a sub-domain level, which was based on self-reported food spending. Thus, based on open-ended questions, our results may be more susceptible to outliers in food spending. Furthermore, we only control for differences in frequency of consumption assuming the same serving sizes for initiative members and non-members and the same production. Thus, we were unable to track potential decreased portion sizes in an effort to decrease food waste etc., which may have potentially influenced the inter-group footprint differences.

Regional Name	Consumption category	Our study, tCO_2eq/cap	95% CI, tCO_2eq/cap	Ivanova and colleagues (2017), tCO_2eq/cap
Galicia (ES)	Food	3.2	2.5 - 3.9	2.5
	Clothing	0.2	0.1 - 0.2	0.4
	Housing	1.8	1.6 - 1.9	1.2
	Transport	4.5	4.0 - 5.2	3.0
Banat-Timis (RO)	Food	2.1	2.0 - 2.2	1.8
	Clothing	0.3	0.2 - 0.3	0.1
	Housing	1.5	1.2 - 1.7	1.3
	Transport	4.1	2.8 - 5.5	1.6
Lazio (IT)	Food	1.6	1.5 - 1.7	1.5
	Clothing	0.3	0.3 - 0.4	0.6
	Housing	2.3	2.1 - 2.5	2.1
	Transport	4.8	4.1 - 5.4	3.3
Saxony-Anhalt (DE)	Food	2.5	2.4 - 2.6	1.5
	Clothing	0.4	0.4 - 0.5	0.5
	Housing	3.2	2.8 - 3.6	3.6
	Transport	4.6	3.2 - 6.0	3.8

SI Table 7: Validity check of footprint results by country and consumption domain with 95% confidence intervals.

We found small differences in absolute terms within the clothing domain, less than 0.3 tCO_2eq/cap across geographical areas. With the exception of the Romanian sample, our calculations were consistently lower than the prior regional assessment. A potential explanation could be that unlike the prior assessment we controlled for the second-hand share of clothing consumption. The share of second-hand clothing consumption reached up to 40% in some regions, thus, causing significant changes to the calculations.

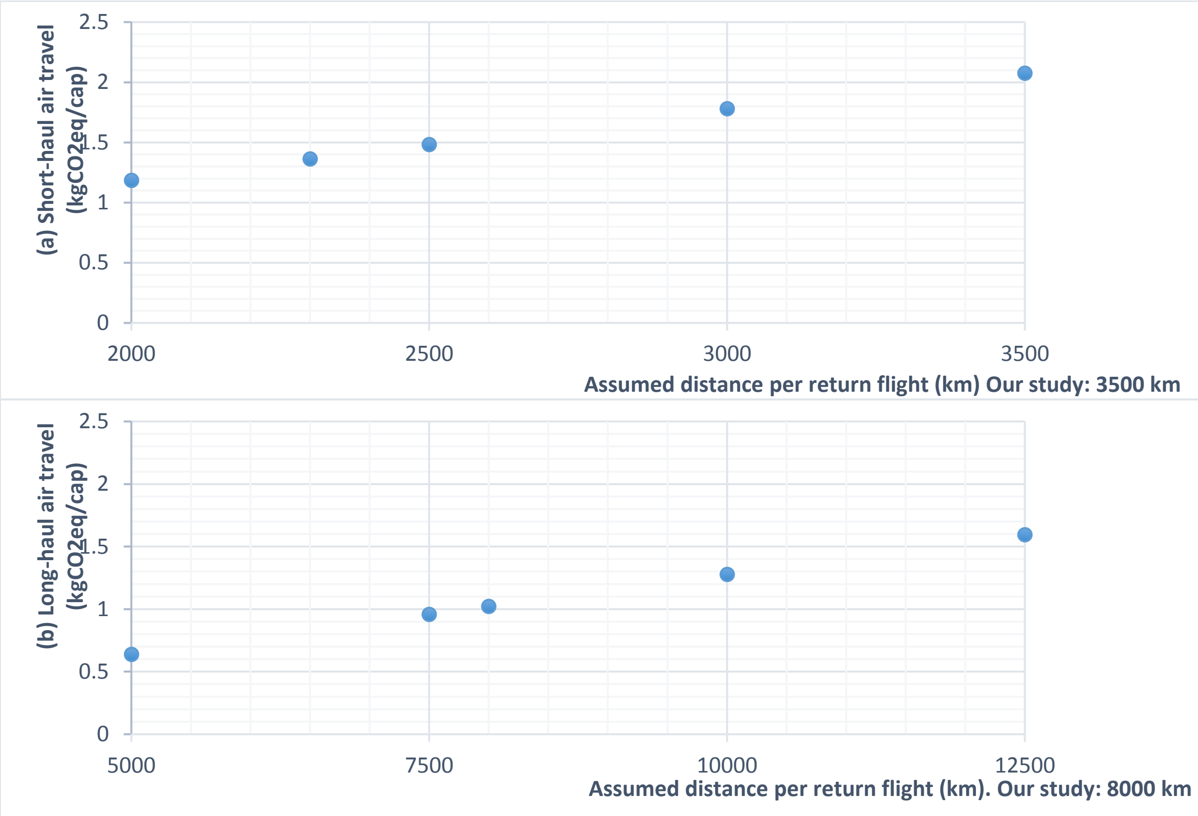
The differences in terms of housing impacts were rather small relative to other domains. In absolute terms they varied between 0.2 and 0.6 tCO_2eq/cap, or between 9 and 33%. The divergence could be attributed to the method of calculations (TABULA sample), self-reported bias, difficulty of response about dwelling characteristics etc.

The highest differences in terms of footprint results was found for the domain of transport. In absolute terms the differences varied between 0.8 and 2.5 tCO_2eq/cap, where we found consistently higher estimates. It could be that our analysis overstated the importance of mobility, while the prior assessment understated it. Particularly, our land-based travel estimate was based on regular weekly travel, scaled to yearly figures by assuming 35 working weeks where travel occurs regularly. Thus, we may have overstated the impact of regular travel with regards to sickness, flexible work, holidays, and change of travel mode etc. The estimates were also based on open questions, where we applied outlier treatment with very conservative thresholds (above 80,000 km/year for land travel and 365 flights/year for air travel). We may have also overstated emissions from shared travel, e.g., no information on the number of people when carpooling.

In the prior regional assessment[4] air-travel emissions (and particularly international emissions) may have been understated due to differences in terms of the principle for allocating emissions. Air transport sectors are potentially more affected by residents' spending abroad and international travel, causing higher uncertainty of results[62].

Choosing a single value of return distance for short- and long-haul flights is critical for the footprint comparison with other consumption domains and assessments. SI Figure 1a compares footprint calculations by varying assumptions about short-haul return flight distance. The blue dots on the figure depict the footprint variation assuming the mean number of flights for the sample (1.95), between 1.2 and 2.1 tCO_2eq/cap for 2000 and 3500 km/return flight, respectively. For comparison, the mean annual number of short-haul return flights is 1.92 and 1.95 for initiative members and non-members, respectively.

Similarly, we depict footprint differences for the mean amount of long-haul return flights, 0.5 return flights/year (SI Figure 1b). The distance of long-haul flights may vary widely. For example, long-haul return flights from the UK may range from 6000 to 30000 km to North Africa and Australia, respectively. The long-haul air travel footprint for the sample average varies between 0.6 and 1.9 tCO_2eq/cap for flight distance between 5000 and 12500 km/return flight. For comparison, the mean annual number of long-haul return flights is 0.85 and 0.48 for initiative members and non-members, respectively.



SI Figure 1: Footprint ranges by various (a) short-haul and (b) long-haul distance assumptions depicted for the sample mean.

Variable definitions, descriptive statistics and hypothesis testing

SI Table 8 provides a list of variable definitions, units, and descriptive statistics between initiative members and non-members samples.

Variable name	Variable definition	Mean	Std. Dev.	Mean INI	Mean REG	Diff	Sign.
INITIATIVE	Initiative members (1), non-members (0), share of initiative members	0.09	0.28	-	-	-	-
TOTAL CF	Total carbon footprint (in tCO_2eq/cap)	9.29	10.43	7.75	9.34	1.64	**
FOOD CF	Food carbon footprint (in tCO_2eq/cap)	2.33	3.70	1.63	2.38	0.75	***
CLOTHING CF	Clothing carbon footprint (in tCO_2eq/cap)	0.26	0.39	0.09	0.28	0.19	***
HOUSING CF	Housing carbon footprint (in tCO_2eq/cap)	2.16	2.40	1.75	2.20	0.45	***
TRANSPORT CF	Transport carbon footprint (in tCO_2eq/cap)	4.60	9.35	4.99	4.56	-0.43	
LS1	"(1) In most ways my life is close to ideal": 7-level categorical variable	4.32	0.04	4.58	4.29	-0.28	**
LS2	"(2) The conditions of my life are excellent": 7-level categorical variable	4.44	0.04	4.74	4.41	-0.34	**
LS3	"(3) I am satisfied with my life": 7-level categorical variable	4.91	0.04	5.20	4.88	-0.32	***
LS4	"(4) So far I have gotten the important things I want from life": 7-level categorical variable	4.78	0.04	4.81	4.78	-0.03	
LS5	"(5) If I could live my life over, I would change almost nothing": 7-level categorical variable	4.32	0.04	4.51	4.31	-0.21	
INCOME	Income category: 6-level categorical variable; (1) for the lowest level of income, (6) for the highest	3.10	1.09	2.67	3.14	0.47	***
HHSIZE	Household size	2.93	1.91	2.72	2.95	0.23	
FEMALE	Female (1), male (0)	0.62	0.49	0.61	0.62	0.01	
AGE	Age category: 3-level categorical variable; (1) for 30 or younger, (2) for 30 to 49 years and (3) for 50 or older	1.99	0.78	2.04	1.98	-0.06	
EDUC	Education category: 6-level categorical variable	5.07	1.14	5.60	5.02	-0.57	***
RURAL	Urban-rural category: 3-level categorical variable; (1) for urban context, (2) for intermediate context and (3) for rural context	1.61	0.80	1.41	1.63	0.08	***
MARRIED	Married (1), Single or other (0)	0.52	0.50	0.50	0.52	0.02	

SI Table 8: Variable definitions and descriptive statistics. Significance level: *p<0.1, **p<0.05, ***p<0.01.

Across carbon footprint variables, we performed a set of one-sided two-sample t-tests using initiative members and non-member groups and tested the difference between the means (N>30) (SI Table 8). We estimated separate variances to control for significant differences in sample sizes between initiative members and non-members. The test assumed that the samples were independent. The hypotheses behind the two-sample t-test were: H_0: $\mu_{region} - \mu_{initiative} = 0$, H_A: $\mu_{region} - \mu_{initiative} > 0$

The alternative hypothesis stated that the difference between regions and initiatives was greater than zero; this would be the case if members of the initiatives actually have lower consumption-related impacts relative to the regions.

Additional two-sided two-sample t-tests were performed for life satisfaction (LS) and socio-demographics factors from our models (H_A: $\mu_{region} - \mu_{initiative} \neq 0$). There were substantial differences in terms of income, education and urban-rural typology across initiatives and the control group.

SI Table 9 presents the CF distribution of initiative members and non-members by country. These results should be interpreted with caution as samples are small and additional socio-demographic differences are not controlled for. See SI Table 14 for country-specific regression output.

Cons. category	**Name**	Galicia (ES)	Banat-Timis (RO)	Lazio (IT)	Saxony-Anhalt (DE)
Food	Initiative members	2.17	1.01	1.25	1.24
	Non-members	3.20	2.09	1.63	2.50
	Diff.	1.04 ***	1.08 ***	0.38 ***	1.26 ***
Clothing	Initiative members	0.09	0.06	0.10	0.09
	Non-members	0.15	0.26	0.31	0.41
	Diff.	0.07***	0.20 ***	0.21 ***	0.31 ***
Housing	Initiative members	1.99	1.98	1.37	1.50
	Non-members	1.77	1.45	2.30	3.19
	Diff.	-0.23	-0.53	0.93 ***	1.69 ***
Transport	Initiative members	4.54	6.57	7.64	2.67
	Non-members	4.59	4.14	4.77	4.60
	Diff.	0.05	-2.43	-2.87	1.93 **

SI Table 9: CF means (in tCO_2eq/cap) by country and consumption domain. Two-sample t test with unequal variances. Ha: diff > 0. Significance level:*p<0.1, **p<0.05, ***p<0.01. Key: No asterisk in "Diff." cells suggests that we cannot reject the hypothesis that the means of initiative member and non-member samples are equal.

In addition, we performed Wilcoxon rank-sum test (also known as the Mann-Whitney two-sample statistic) and a nonparametric *k*-sample test on the equality of medians to address concerns about the difference in sample sizes and non-normal distribution[63,64]. The median test indicated that the medians for food and clothing CF were significantly different, while those for housing and transport were not statistically different at any level lower than 5% (SI Table 10). The Wilcoxon-Mann-Whitney test confirmed the conclusions for most domains except for housing (at the 5% significance level).

Consumption domain	**Wilcoxon–Mann–Whitney test**	**Nonparametric *k*-sample test on the equality of medians**
Food	0.000	0.000
Clothing	0.000	0.000
Housing	0.041	0.079
Transport	0.657	0.451

SI Table 10: P-values from nonparametric tests

The regression model and behavioral validation

OLS regressions

The model:

$$ln(\widehat{CF_i}) = \beta_0 + \beta_1(INITIATIVE_i) + \beta_2(INCOME_i) + \beta_3(HHSIZE_i) + \beta_4(FEMALE_i) + \beta_5(AGE_i) + \beta_6(EDUC_i) + \beta_7(RURAL_i)$$

$$+\beta_8(MARRIED_i) + \beta_{11}(ES_i) + \beta_{12}(RO_i) + \beta_{13}(IT_i) + \epsilon_i$$

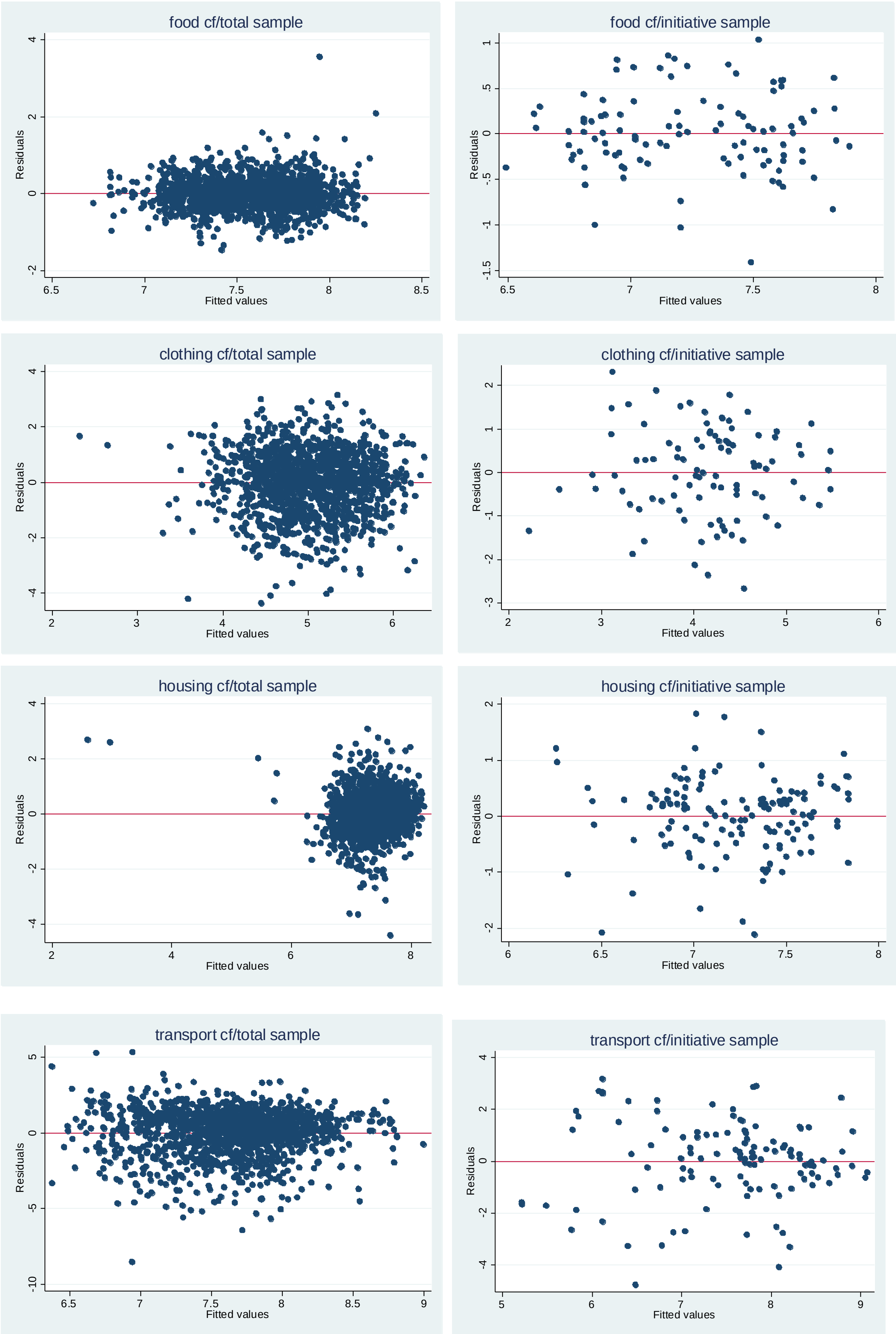
Taking the differential with respect to the initiative membership $\left(\frac{\partial}{\partial INI}\right) ln(CF)$ we got:

$$\frac{\mathrm{d}CF}{CF} = \mathrm{d}INITIATIVE * \beta_1$$

The first component referred to the percent change of footprint in, while the second to the change in the initiative variable times its coefficient. If we multiplied by 100, we would get the percent change in the carbon footprint: $\%\Delta CF = 100 * \mathrm{d}INITIATIVE * \beta_1$

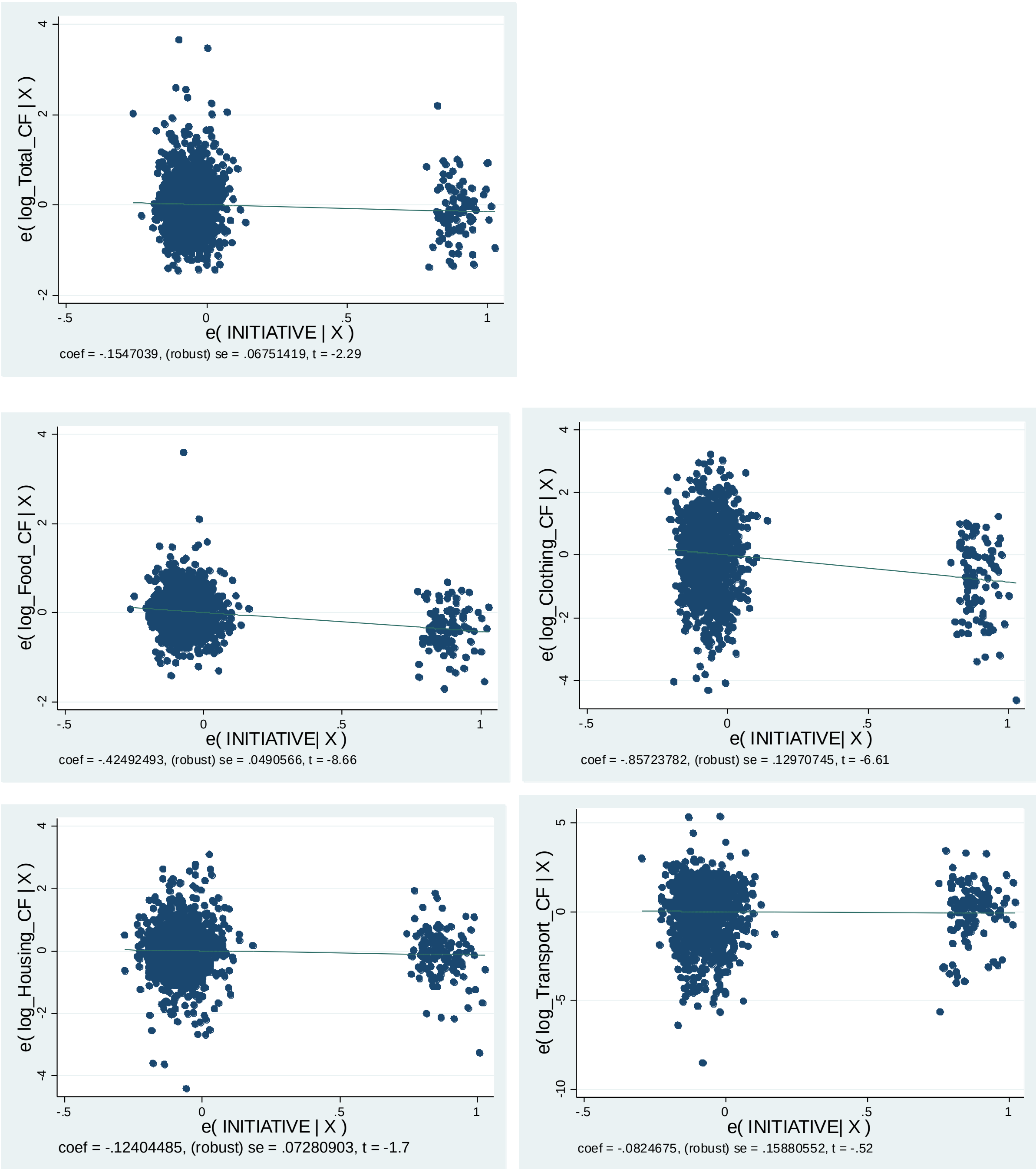
1.1.1. Assumptions

We checked some of the underlying assumptions for the regression analysis. First, in SI Figure 2 we plotted the residuals against the fitted values for each of the main regression models displayed in Table 1 in the main text (least-squares assumption). We find no visible patterns on the plots, which should be the case for well-fitted models.



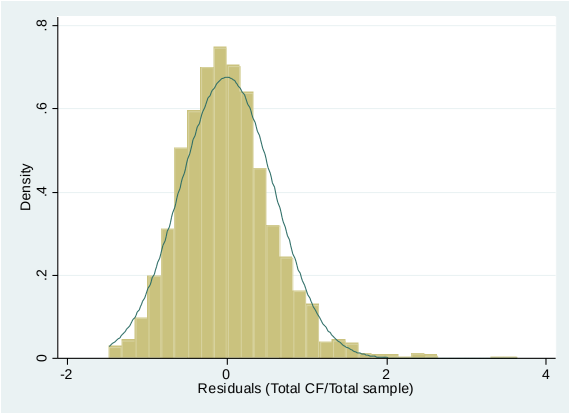
SI Figure 2: Plots of residuals against fitted values across the regression models in Table 1.

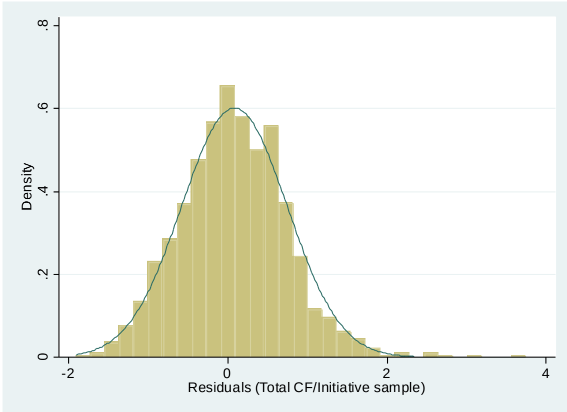
Furthermore, there needs to be a linear relationship between the dependent variable (*CF*) and the independent variable of interest, *INITIATIVE*. We tested this assumption using partial regression plots (SI Figure 3). The categorical nature of the variables added some difficulty to the interpretation of results; however, we found no major causes of concern for the *INITIATIVE* coefficient.

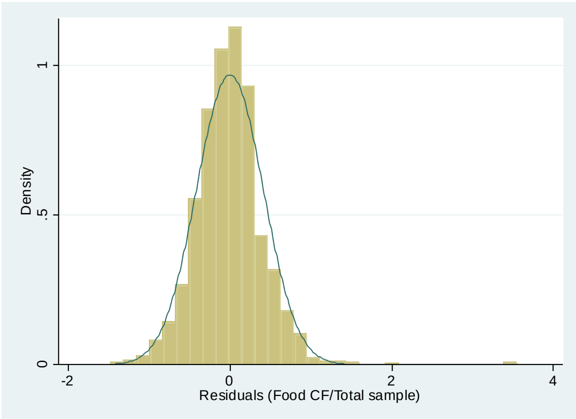


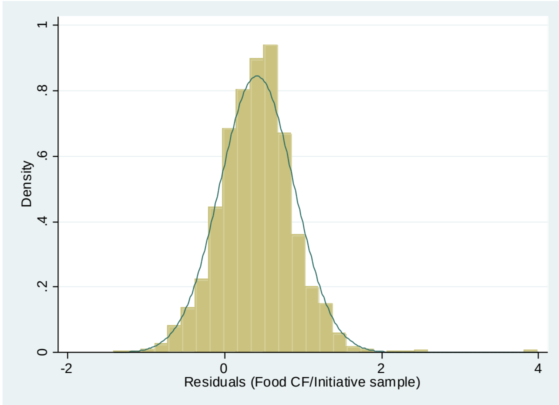
SI Figure 3: Partial regression plots for the *INIATIVE* coefficient. The regression models are depicted in Table 1 and are based on the total sample (initiative members and non-members).

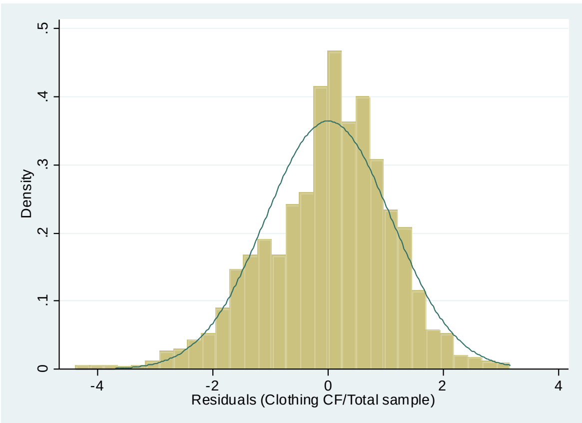
We further tested for multicollinearity (SI Table 12) and the normality of residuals (SI Figure 4). No major concerns arose from the analysis.

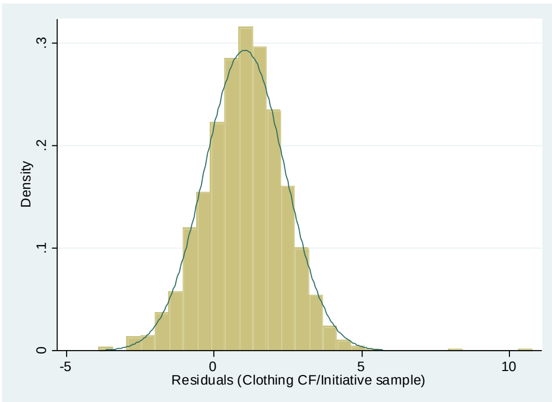

Density
Residuals (Total CF/Total sample)

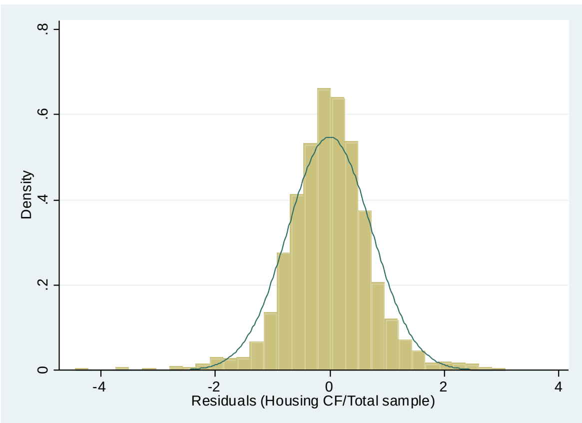

Density
Residuals (Total CF/Initiative sample)

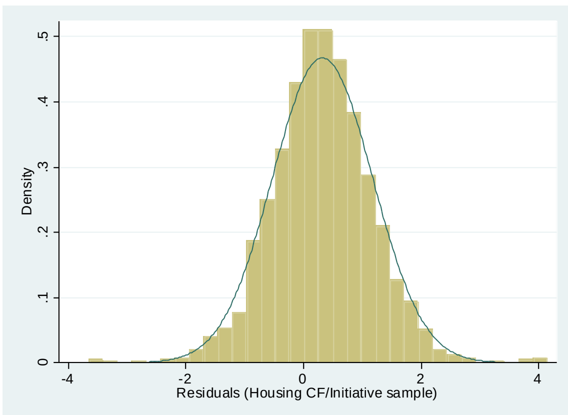

Density
Residuals (Food CF/Total sample)

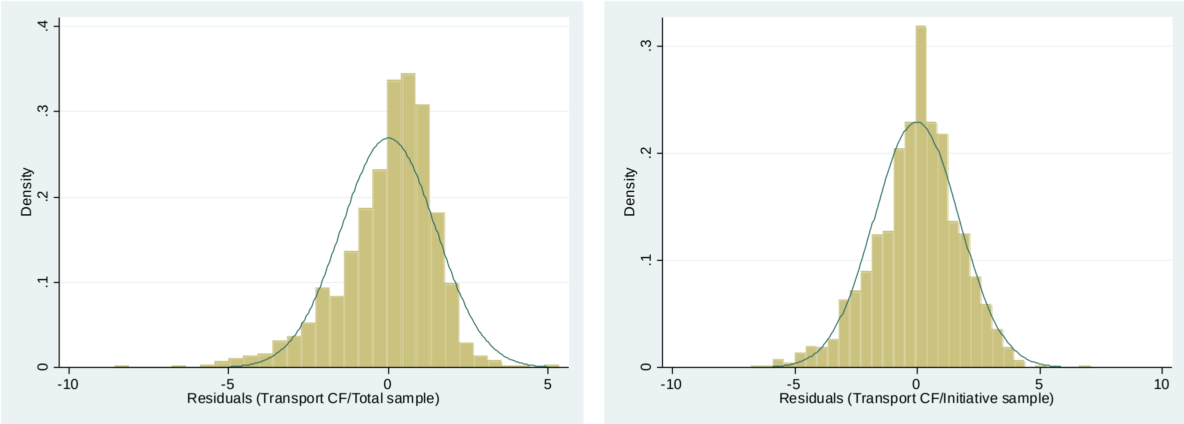

Density
Residuals (Food CF/Initiative sample)


Density
Residuals (Clothing CF/Total sample)


Density
Residuals (Clothing CF/Initiative sample)


Density
Residuals (Housing CF/Total sample)


Density
Residuals (Housing CF/Initiative sample)



SI Figure 4: Distribution of residuals plotted against normal distribution.

Pairwise correlation coefficients and their significance between the explanatory variables is presented in SI Table 11. The correlation table highlighted specific relationships between the explanatory factors, where caution was needed when interpreting regression coefficients. It was also useful for profiling of initiative members.

		1	2	3	4	5	6	7	8
INITIATIVE	1	1.000							
INCOME	2	-0.119*	1.000						
HHSIZE	3	-0.034	0.121*	1.000					
FEMALE	4	-0.008	-0.092*	0.052*	1.000				
AGE	5	0.020	0.163*	-0.267*	-0.149*	1.000			
EDUC	6	0.141*	0.193*	-0.034	-0.038	0.026	1.000		
RURAL	7	-0.078*	0.044	0.065*	0.007	0.077*	-0.158*	1.000	
MARRIED	8	-0.009	0.272*	0.028	-0.106*	0.440*	0.011	0.102*	1.000

SI Table 11: Pair-wise correlation coefficients of socio-demographic factors included in the regression analysis. Stars indicate 95% significance.

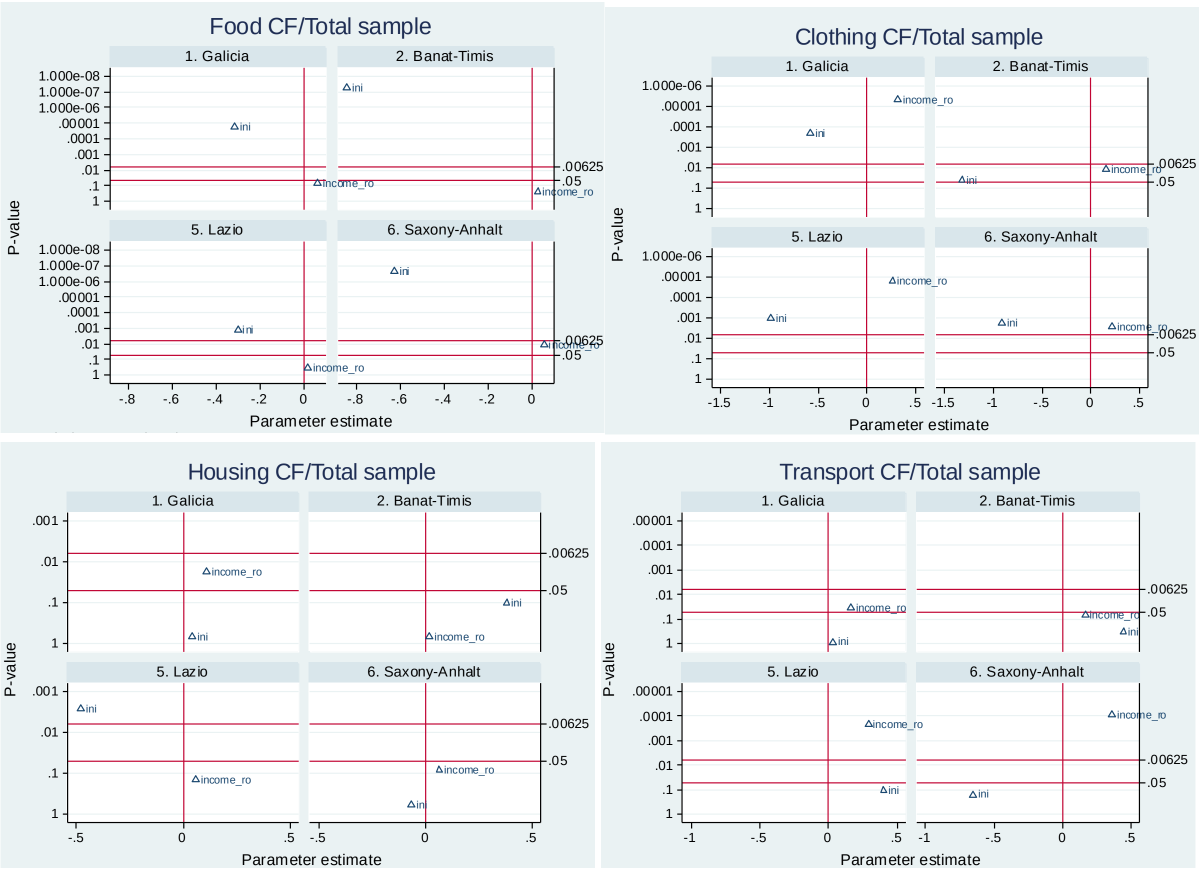
Variable	**VIF**	**1/VIF**
ES	2.30	0.435
IT	2.05	0.487
RO	1.94	0.516
AGE	1.75	0.571
MARRIED	1.40	0.716
INCOME	1.26	0.797
EDUC	1.22	0.820
HHSIZE	1.20	0.833
RURAL	1.13	0.883
INITIATIVE	1.05	0.950
FEMALE	1.03	0.967
Mean VIF	**1.49**	

SI Table 12: Variance inflation factors and tolerance value to infer about multicollinearity check in relation to table 1.

As we incorporated a large number of socio-demographic factors, we additionally performed tests for multicollinearity, or the potential for instability of the coefficients and their "inflated" variance[65,66]. SI Table 12 reports different measures of collinearity (variance inflation factor (VIF) and tolerance values) on the total footprint regression (see Table 1 in the main text). It pointed to no strong evidence for multicollinearity. As a rule of thumb, variables with VIF values greater than 10 may merit further investigation with regards to multicollinearity issues[65]. A tolerance value lower than 0.1 is comparable to a VIF of 10.

We further measured practical and statistical significance of the *INITIATIVE* coefficient using multiple smile plots by geographical areas. The X-axis depicts practical significance with the reference line indicating the null hypothesis. The Y-axis depicts statistical significance with the reference lines indicating uncorrected and Šidák-corrected threshold P-values (*smileplot* package, Stata).

SI Figure 5 presents smile plots depicting the practical and statistical significance of the *INITIATIVE* and *INCOME* coefficients in the food, clothing, housing and transport CF models displayed on table 1. In the context of food and clothing, the *INITIATIVE* coefficient appeared in the upper left corner for most geographical areas, signaling for a high practical and statistical significance. The effect was found below the statistical thresholds for the models on housing and transport CF.



SI Figure 5: Practical and statistical significance by geographical area.

1.1.2. Detailed results

SI Table 13 (a) and (b) present our findings on a consumption sub-domain level for the total and initiative samples, respectively. Note that the sub-domain level models may differ in sample sizes relative to the domain-level models. First, we transformed dependent variables into logarithmic form to normalize their distribution, thus, omitting zero values from observations. Second, there may be differences in missing values across domains. Missing values were omitted in all footprint summations.

(a) TOTAL	Meat CF	Dairy products CF	Vegetables and fruits CF	Other food CF	Electricity CF	Space heating CF	Water heating CF	Car travel CF	Non-car travel CF	Air travel CF
INITIATIVE	-0.324***	-0.309***	0.227***	-0.332***	0.122	-0.151	0.054	-0.043	-0.103	0.022
	(0.07)	(0.07)	(0.03)	(0.06)	(0.09)	(0.10)	(0.08)	(0.14)	(0.26)	(0.12)
INCOME	-0.020	0.064***	0.050***	0.071***	0.074***	0.090***	-0.030	0.094**	0.033	0.054
	(0.01)	(0.01)	(0.01)	(0.02)	(0.02)	(0.03)	(0.03)	(0.04)	(0.07)	(0.03)
HHSIZE	0.002	-0.002	-0.001	-0.022*	-0.153***	-0.119***	-0.067**	-0.020	-0.010	-0.007
	(0.01)	(0.01)	(0.01)	(0.01)	(0.04)	(0.03)	(0.03)	(0.03)	(0.03)	(0.02)
FEMALE	-0.340***	-0.109***	-0.091***	-0.114***	0.029	-0.041	-0.053	-0.324***	0.223	-0.151**
	(0.03)	(0.03)	(0.02)	(0.03)	(0.04)	(0.06)	(0.04)	(0.08)	(0.16)	(0.07)
AGE	-0.014	0.029	0.126***	0.055**	0.121***	0.270***	0.127***	0.025	-0.238*	0.041
	(0.02)	(0.02)	(0.02)	(0.03)	(0.04)	(0.05)	(0.04)	(0.06)	(0.12)	(0.05)
EDUC	-0.047***	-0.007	-0.022**	-0.013	0.016	0.004	0.025	0.057	0.007	0.066*
	(0.01)	(0.01)	(0.01)	(0.01)	(0.02)	(0.03)	(0.02)	(0.04)	(0.08)	(0.03)
RURAL	0.026	0.010	-0.001	-0.014	0.134***	0.071*	-0.156***	0.278***	0.070	-0.040
	(0.02)	(0.02)	(0.01)	(0.02)	(0.03)	(0.04)	(0.03)	(0.05)	(0.10)	(0.04)
MARRIED	0.091***	0.024	0.070***	0.095***	-0.079	-0.349***	-0.180***	0.091	-0.161	-0.134*
	(0.03)	(0.03)	(0.03)	(0.03)	(0.05)	(0.07)	(0.05)	(0.09)	(0.18)	(0.07)
Country effects	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
AdjustedR^2	0.283	0.532	0.266	0.135	0.410	0.173	0.088	0.086	0.158	0.029
Obs.	1497	1519	1572	1582	1465	1512	1604	1124	721	792
(b) INITIATIVE	Meat CF	Dairy products CF	Vegetables and fruits CF	Other food CF	Electricity CF	Space heating CF	Water heating CF	Car travel CF	Non-car travel CF	Air travel CF
INCOME	-0.018	0.003	0.027	0.062	-0.111	-0.020	-0.095	0.148	0.144	0.045
	(0.11)	(0.06)	(0.03)	(0.07)	(0.09)	(0.11)	(0.07)	(0.17)	(0.24)	(0.11)
HHSIZE	-0.003	0.044	-0.006	-0.028	-0.111**	-0.091*	-0.081	-0.072	-0.006	0.020
	(0.05)	(0.03)	(0.02)	(0.03)	(0.05)	(0.05)	(0.05)	(0.05)	(0.15)	(0.06)
FEMALE	-0.256*	0.071	-0.147***	-0.063	-0.040	0.031	0.053	-0.746**	0.063	0.068
	(0.13)	(0.14)	(0.05)	(0.12)	(0.13)	(0.18)	(0.14)	(0.30)	(0.54)	(0.23)
AGE	-0.015	0.068	0.110**	0.164	0.277**	0.153	0.006	-0.414	-0.102	-0.222
	(0.12)	(0.12)	(0.05)	(0.11)	(0.12)	(0.17)	(0.14)	(0.25)	(0.54)	(0.22)
EDUC	-0.122	-0.113	-0.027	-0.051	-0.082	0.277*	0.249	0.029	0.063	0.058
	(0.09)	(0.09)	(0.03)	(0.08)	(0.09)	(0.16)	(0.16)	(0.19)	(0.32)	(0.16)
RURAL	-0.095	-0.124	-0.002	-0.018	-0.042	-0.311*	-0.188	-0.055	1.043***	0.116
	(0.13)	(0.10)	(0.03)	(0.09)	(0.13)	(0.18)	(0.13)	(0.20)	(0.39)	(0.19)
MARRIED	0.273	0.405***	0.105*	-0.044	-0.119	-0.326	-0.152	-0.004	-0.328	-0.111
	(0.17)	(0.13)	(0.06)	(0.13)	(0.15)	(0.21)	(0.13)	(0.31)	(0.64)	(0.28)
Country effects	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
AdjustedR^2	0.034	0.473	0.177	0.114	0.154	0.193	0.064	0.096	0.110	-0.125
Obs.	78	107	119	111	111	119	131	81	76	72

SI Table 13: Socio-economic determinants of the carbon footprint of the (a) total sample (initiative members and non-members) and (b) the initiative sample (b/se). Dependent variables in logarithmic form, by sub-consumption domain. Robust standard errors in parenthesis. Non-car refers to public and active travel. Significance level: *p<0.1, **p<0.05, ***p<0.01.

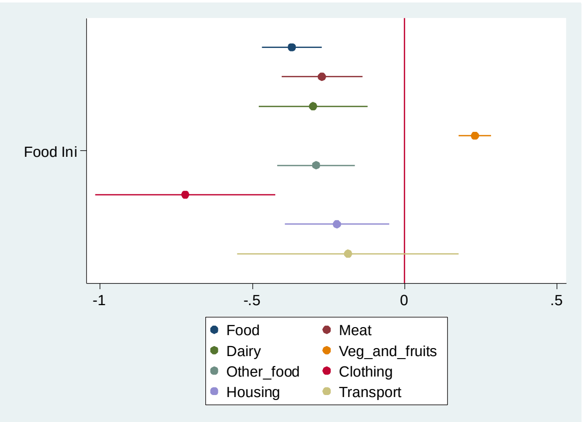
Finally, we checked the sensitivity of our findings across countries (SI Table 14). It should be noted that the size of initiatives is below 30 for IT and RO initiative samples. Our conclusions with regards to the *INITIATIVE* coefficient were generally confirmed across countries.

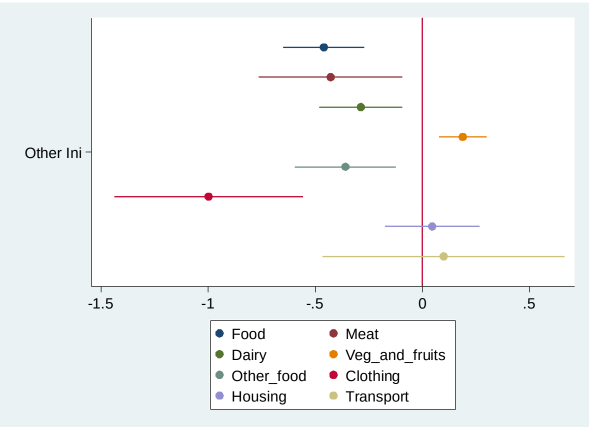
The *INITIATIVE* coefficient was confirmed to be negative and highly significant across all country samples for food, varying between -0.30 and -0.84 (SI Table 14a). Similarly, our results were confirmed for the *INITIATIVE* coefficient in the clothing models, where we found negative and significant coefficients between -0.58 and -1.32 (SI Table 14b). SI Table 14c confirmed our housing conclusions across the countries, with the exception of the Italian sample. Initiative members in Lazio were noted to have 48% lower shelter impacts. Finally, the *INITIATIVE* coefficient was insignificant across all country samples in the transport model (SI Table 14d).

The *INCOME* effect was generally confirmed across country samples, with clothing and transport standing out as income-elastic consumption categories.

	(a) Food					(b) Clothing				
	TOTAL	**ES**	**RO**	**IT**	**DE**	**TOTAL**	**ES**	**RO**	**IT**	**DE**
INITIATIVE	-0.425***	-0.314***	-0.844***	-0.301***	-0.628***	-0.857***	-0.583***	-1.320**	-0.986***	-0.913***
	(0.05)	(0.07)	(0.15)	(0.09)	(0.12)	(0.13)	(0.16)	(0.64)	(0.30)	(0.29)
INCOME	0.048***	0.063*	0.026	0.017	0.054**	0.225***	0.314***	0.154**	0.258***	0.214***
	(0.01)	(0.03)	(0.02)	(0.02)	(0.02)	(0.03)	(0.07)	(0.06)	(0.06)	(0.07)
HHSIZE	-0.010*	-0.010*	-0.006	0.016	-0.008	-0.061***	-0.042**	-0.023	-0.131**	-0.190**
	(0.01)	(0.01)	(0.02)	(0.02)	(0.03)	(0.02)	(0.02)	(0.05)	(0.05)	(0.08)
FEMALE	-0.179***	-0.174***	-0.129**	-0.245***	-0.164***	0.026	-0.025	-0.098	0.021	0.124
	(0.02)	(0.05)	(0.06)	(0.04)	(0.04)	(0.06)	(0.11)	(0.16)	(0.12)	(0.12)
AGE	0.064***	0.076**	0.090*	0.062**	-0.045	0.103**	0.234***	-0.411**	0.056	0.092
	(0.02)	(0.04)	(0.05)	(0.03)	(0.04)	(0.05)	(0.09)	(0.16)	(0.09)	(0.13)
EDUC	-0.024***	-0.020	0.043	-0.021	-0.019	0.077**	0.060	0.142	0.107	0.092**
	(0.01)	(0.02)	(0.03)	(0.02)	(0.01)	(0.03)	(0.07)	(0.10)	(0.07)	(0.04)
RURAL	0.003	-0.043	-0.047	-0.002	0.074***	-0.017	-0.046	-0.088	-0.001	0.024
	(0.01)	(0.03)	(0.03)	(0.03)	(0.02)	(0.04)	(0.07)	(0.10)	(0.09)	(0.07)
MARRIED	0.099***	0.158***	0.045	0.014	0.095*	-0.016	-0.203	0.166	-0.009	0.258*
	(0.02)	(0.05)	(0.06)	(0.04)	(0.06)	(0.07)	(0.13)	(0.19)	(0.12)	(0.16)
Country effects	YES	-	-	-	-	YES	-	-	-	-
Constant	7.576***	7.778***	7.254***	7.353***	7.680***	4.389***	3.263***	4.569***	4.209***	4.354***
	(0.08)	(0.17)	(0.17)	(0.14)	(0.15)	(0.23)	(0.40)	(0.48)	(0.47)	(0.49)
AdjustedR2	0.293	0.128	0.166	0.129	0.335	0.183	0.113	0.057	0.102	0.177
Observations	1569	473	281	450	365	1432	439	253	392	348
	(c) Housing					**(d) Transport**				
	TOTAL	**ES**	**RO**	**IT**	**DE**	**TOTAL**	**ES**	**RO**	**IT**	**DE**
INITIATIVE	-0.124*	0.043	0.379	-0.481***	-0.066	-0.082	0.034	0.442	0.403	-0.650
	(0.07)	(0.10)	(0.23)	(0.16)	(0.12)	(0.16)	(0.20)	(0.47)	(0.25)	(0.46)
INCOME	0.045**	0.108**	0.018	0.058	0.064*	0.248***	0.162**	0.163*	0.291***	0.356***
	(0.02)	(0.05)	(0.04)	(0.04)	(0.04)	(0.04)	(0.08)	(0.09)	(0.08)	(0.09)
HHSIZE	-0.115***	-0.078***	-0.148***	-0.242***	-0.249***	-0.028	0.005	-0.018	-0.055	-0.072
	(0.03)	(0.02)	(0.04)	(0.03)	(0.04)	(0.02)	(0.02)	(0.06)	(0.06)	(0.09)
FEMALE	-0.007	-0.120*	0.073	0.003	0.083	-0.227***	-0.022	-0.548**	-0.219*	-0.224
	(0.04)	(0.07)	(0.10)	(0.07)	(0.07)	(0.08)	(0.15)	(0.21)	(0.13)	(0.18)
AGE	0.227***	0.230***	0.118	0.071	0.284***	-0.113*	-0.195*	-0.221	-0.201**	-0.065
	(0.04)	(0.06)	(0.08)	(0.05)	(0.08)	(0.06)	(0.12)	(0.19)	(0.10)	(0.20)
EDUC	-0.000	-0.002	0.116**	-0.023	-0.045*	0.140***	0.295***	0.113	0.354***	-0.026
	(0.02)	(0.04)	(0.05)	(0.04)	(0.02)	(0.04)	(0.08)	(0.12)	(0.07)	(0.06)
RURAL	0.089***	0.044	0.142**	0.086*	0.104**	0.171***	-0.009	-0.007	0.251***	0.261***
	(0.03)	(0.05)	(0.06)	(0.05)	(0.04)	(0.05)	(0.09)	(0.14)	(0.09)	(0.10)
MARRIED	-0.157***	-0.230***	-0.152	-0.037	-0.113	0.049	0.293*	-0.043	-0.064	-0.109
	(0.05)	(0.08)	(0.11)	(0.08)	(0.08)	(0.09)	(0.16)	(0.24)	(0.14)	(0.24)
Country effects	YES	-	-	-	-	YES	-	-	-	-
Constant	7.217***	6.873***	6.348***	7.856***	7.403***	6.139***	5.931***	6.936***	5.448***	6.514***
	(0.15)	(0.25)	(0.33)	(0.28)	(0.24)	(0.29)	(0.56)	(0.66)	(0.47)	(0.74)
AdjustedR2	0.226	0.134	0.115	0.143	0.299	0.069	0.040	0.026	0.134	0.088
Observations	1607	484	288	458	377	1446	419	261	424	342

SI Table 14: Sensitivity check of socio-economic determinants of (a) food, (b) clothing, (c) housing, and (d) transport carbon footprint across countries (b/se). Robust standard errors in parenthesis. Significance level: *p<0.1, **p<0.05, ***p<0.01.





SI Figure 6: Main domain results shown for initiatives with an exclusive focus on the food domain (on the left) and other initiatives (on the right). Food initiatives include Zocamiñoca (ES) and the Italian network of agricultural cooperatives.

We separately analysed the sub-sample of food-specific initiatives including *Zocamiñoca* (ES), *Lebensmittel retten Magdeburg* (DE) and the Italian network of agricultural cooperatives (SI Figure 6, on the left). SI Figure 6, on the right, depicts results for the rest of initiatives, which may also have food focus, e.g. comprehensive initiatives such as ecovillages and the Transition Town movement. We observed the same trends overall between food-specific and other initiatives, with the exception of the "Housing" coefficient, which was negative and significant for food-specific initiatives. The initiative sub-samples are relatively small, 81 and 60 members for food-specific and other initiatives, respectively.

1.1.3. Consumption and behavioral validation

We explored the *INITIATIVE* coefficient on consumption (behavior) variables included in the questionnaire. Note that there are substantial differences in the scale of dependent variables and a varying model fit (SI Table 15). We confirmed that the footprint differences noted in the main text are also present in the consumption data.

We found that there were significant differences in terms food and clothing consumption between initiative members and non-members (SI Table 15a). Initiative members demonstrated less frequent consumption of beef, pork, chicken, dairy products, and processed food (and more frequent consumption of fruits and vegetables). Frequency of consumption was measured in terms of days per week. Initiative members further demonstrated lower expenditure in store-bought food, although the coefficient was only partially significant. Thus, initiative members spent 15 EUR less in a week (780 EUR/year) compared to their socio-demographic counterparts, on average.

In terms of clothing, initiatives showed lower spending (SI Table 15a). Particularly, initiative members spent about 340 EUR/year less on clothing relative to their socio-demographic counterparts. They also had a much higher share of second-hand clothing consumption, about 147% higher on average.

(a) Food and Clothing CF	Beef consumption	Pork consumption	Chicken consumption	Dairy products consumption	Processed food consumption	Vegetables and fruits consumption	Weekly spending on store-bought food	Annual spending on clothing	Share of second-hand clothing
INITIATIVE	-0.336***	-0.786***	-1.115***	-1.094***	-0.396***	0.809***	-14.832*	-338.66***	1.474***
	(0.07)	(0.09)	(0.10)	(0.20)	(0.10)	(0.09)	(7.82)	(56.20)	(0.18)
INCOME	-0.004	-0.075***	-0.063**	0.147***	0.025	0.161***	17.192**	134.133***	-0.128***
	(0.02)	(0.03)	(0.03)	(0.05)	(0.03)	(0.04)	(7.49)	(41.80)	(0.05)
HHSIZE	-0.003	0.006	0.002	0.006	-0.026	-0.001	-2.800**	-45.065**	0.068**
	(0.01)	(0.01)	(0.01)	(0.02)	(0.02)	(0.03)	(1.40)	(19.02)	(0.03)
FEMALE	-0.224***	-0.359***	-0.006	0.278***	-0.203***	0.454***	3.109	228.478	0.441***
	(0.04)	(0.06)	(0.06)	(0.09)	(0.07)	(0.07)	(9.09)	(142.03)	(0.08)
AGE	0.008	-0.121***	-0.201***	-0.067	-0.174***	0.284***	11.326***	145.375	-0.106
	(0.04)	(0.04)	(0.05)	(0.08)	(0.05)	(0.06)	(3.88)	(179.39)	(0.07)
EDUC	-0.028	-0.082***	-0.077***	0.044	-0.086***	0.015	1.006	-49.202	-0.054
	(0.02)	(0.03)	(0.03)	(0.04)	(0.03)	(0.03)	(2.05)	(98.06)	(0.04)
RURAL	0.005	0.107***	0.043	-0.045	-0.054	-0.047	-5.554	-24.668	0.026
	(0.03)	(0.04)	(0.04)	(0.06)	(0.04)	(0.05)	(5.46)	(26.74)	(0.05)
MARRIED	0.112**	0.179***	0.068	-0.006	-0.277***	0.132	25.866**	-260.758	-0.100
	(0.05)	(0.06)	(0.07)	(0.10)	(0.08)	(0.08)	(11.04)	(274.95)	(0.10)
Country effects	YES	YES	YES	YES	YES	YES	YES	YES	YES
Adjusted R^2	0.084	0.122	0.180	0.223	0.137	0.102	0.020	0.003	0.156
Obs.	1603	1601	1601	1603	1599	1604	1597	1595	1605

(b) Housing CF	Home surface	Time of construction	Annual electricity spending	Home temperature in winter	Space heating needs	Carbon intensity space heating	Water heating needs	Carbon intensity water heating
INITIATIVE	-12.079	-0.165	-13.105	-0.922***	-473.832*	-0.016	15.456	0.006
	(9.51)	(0.12)	(45.15)	(0.16)	(273.04)	(0.01)	(12.65)	(0.01)
INCOME	14.884***	0.045	18.132*	0.257***	306.894*	-0.002	-10.419***	-0.004
	(3.52)	(0.03)	(10.53)	(0.05)	(170.57)	(0.00)	(3.96)	(0.00)
HHSIZE	4.690	-0.018	-42.972***	-0.021	-319.828***	-0.003	-43.342***	-0.002
	(2.98)	(0.02)	(14.14)	(0.03)	(102.55)	(0.00)	(15.76)	(0.00)
FEMALE	-6.395	0.012	2.734	0.224**	-148.596	0.001	-7.823	0.004
	(8.23)	(0.06)	(31.06)	(0.09)	(365.65)	(0.01)	(7.16)	(0.01)
AGE	-4.022	-0.185***	55.597***	-0.005	579.965**	0.006	67.835***	0.008
	(5.42)	(0.05)	(20.48)	(0.08)	(230.79)	(0.01)	(11.43)	(0.01)
EDUC	-6.020	-0.028	-0.832	-0.154***	-257.390	-0.002	9.916***	0.003
	(3.75)	(0.03)	(16.88)	(0.04)	(178.35)	(0.00)	(2.93)	(0.00)
RURAL	31.336***	0.036	44.896***	-0.043	1402.386***	-0.046***	-7.573*	-0.021***
	(5.10)	(0.04)	(14.47)	(0.06)	(236.97)	(0.00)	(4.44)	(0.01)

MARRIED	5.994	0.148**	-64.559**	0.248**	-905.556***	-0.013*	-115.655***	-0.024***
	(6.79)	(0.07)	(31.36)	(0.10)	(302.92)	(0.01)	(13.63)	(0.01)
Country effects	YES	YES	YES	YES	YES	YES	YES	YES
AdjustedR2	0.060	0.113	0.125	0.268	0.086	0.107	0.493	0.030
Observations	1606	1604	1470	1605	1599	1512	1607	1604

Transport CF	Car ownership and sole use	Car ownership and shared use	Annual car-travelled distance	Annual active travelled distance	Annual total distance by land	Number of short flights	Number of long flights
INITIATIVE	-0.078*	-0.054	-981.405	1786.263**	1219.758	-23.564	-13.914
	(0.04)	(0.04)	(642.67)	(718.42)	(1219.97)	(16.67)	(13.70)
INCOME	0.029**	0.005	954.243***	-6.538	1120.279***	-10.324	-7.778
	(0.01)	(0.01)	(265.36)	(98.85)	(357.47)	(10.29)	(11.43)
HHSIZE	-0.034***	0.043***	-134.387	18.546	-182.895	-0.178	-1.089
	(0.01)	(0.01)	(169.46)	(47.39)	(235.32)	(2.57)	(3.41)
FEMALE	-0.096***	0.082***	-1767.889***	-494.394**	-2188.391***	-9.872	-1.486
	(0.02)	(0.03)	(482.36)	(229.13)	(680.87)	(16.53)	(17.17)
AGE	0.084***	-0.029	219.715	108.457	-537.775	6.800	0.386
	(0.02)	(0.02)	(354.00)	(175.41)	(517.59)	(12.57)	(14.46)
EDUC	0.039***	-0.016	179.381	306.060***	466.440	8.045	6.830
	(0.01)	(0.01)	(222.84)	(101.11)	(313.28)	(5.79)	(5.72)
RURAL	0.049***	0.016	2183.193***	-134.117	1891.387***	-9.735*	-3.142
	(0.02)	(0.02)	(332.15)	(136.12)	(456.78)	(5.83)	(5.78)
MARRIED	-0.081***	0.174***	1015.080**	-283.283	-19.589	25.178*	7.857
	(0.03)	(0.03)	(478.36)	(240.97)	(749.05)	(13.16)	(12.89)
Country effects	YES	YES	YES	YES	YES	YES	YES
AdjustedR^2	0.091	0.076	0.098	0.042	0.038	0.001	-0.003
Obs.	1607	1607	1552	1552	1552	1474	1410

SI Table 15: Socio-economic determinants of (a) food and clothing, (b) housing, and (c) transport consumption of the total sample (initiative members and non-members) (b/se). Robust standard errors in parenthesis. Active travel refers to distance by walking, Significance level: *p<0.1, **p<0.05, ***p<0.01.

In terms of housing, we find no significant differences in dwelling characteristics (home surface and time of construction), or the annual amount paid for electricity (in EUR/cap) (SI Table 15b). We measured home surface in m^2 and time of construction as a categorical variable with the following values (1. Before 1900, 2. 1900-1945, 3. 1945-1970, 4. 1970-1990, 5.1990-2000, 6.After 2000). In terms of space and water heating, we found no significant differences between initiative members and non-members with regards to both heating needs (measured in kWh/year/cap) and choice of heating source (and hence carbon intensity of heating measured in $kgCO_2eq/kWh$). However, we found that initiative members differed in their temperature preferences in the winter, with them tolerating close to 1°C colder temperatures.

Finally, we found no differences in terms of car ownership and use, and air travel (in terms of annual number of fights) (SI Table 15c). We also tested the importance of *INITIATIVE* coefficient for the annual travelled distance by car and all land-based transportation modes (in km/cap), where we found the coefficient to be insignificant again.

Propensity score matching

We further compared our results obtained through multivariate regression with propensity score matching analysis, which by reducing the covariates into a single score, may present a statistical advantage and a greater credibility to our results. Results obtained from both methods are compared in SI Table 16. The propensity score matching analysis uses the *teffects* command in Stata. The coefficients from the propensity score matching analysis were comparable to our regression estimates, with all OLS coefficients contained in the 95% CIs.

INITIATIVE	Propensity score matching analysis	95% confidence intervals	OLS coefficients (Table 1)
Food CF	-.314***	-.463 -.166	-.424***
Clothing CF	-1.16***	-1.523 -.805	-.857***
Housing CF	-.426**	-.743 -.110	-.124*
Transport CF	.191	-.180 .562	-.082

SI Table 16: Propensity score matching analysis including 95% confidence intervals. Significance level: *p<0.1, **p<0.05, ***p<0.01.

OLOGIT regressions

1.1.4. Assumptions

The LS items in our survey were assumed to be categorical and ordered, thus, requiring a different handling – ordinal logistic (logit) regression model. For a single LS item the measurement model is the following:

$$LS_i = m \ \ if \ \ \tau_{m-1} \leq LS_i^* \leq \tau_m \text{ for } m = 1 \ to \ J$$

Where cut points $\tau_1$through τ_{J-1}, J as the number of ordinal categories, and $\tau_0 = -\infty$ and $\tau_J = \infty$ were estimated[67]. With seven outcomes, we estimated the following model for each LS item:

$$\Pr(LS \leq 1|\boldsymbol{x}) = F(\tau_1 - \beta x)$$

$$\Pr(LS \leq 2|\boldsymbol{x}) = F(\tau_2 - \beta x)$$

$$\Pr(LS \leq 3|\boldsymbol{x}) = F(\tau_3 - \beta x)$$

$$\Pr(LS \leq 4|\boldsymbol{x}) = F(\tau_4 - \beta x)$$

$$\Pr(LS \leq 5|\boldsymbol{x}) = F(\tau_5 - \beta x)$$

$$\Pr(LS \leq 6|\boldsymbol{x}) = F(\tau_6 - \beta x)$$

A main assumption of the ordinal logit model is the *proportional odds assumption*, according to which the probability curves are parallel as a consequence of the assumption that β's are equal for each equation[67]. We tested the validity of this assumption using the *omodel* command in Stata, computing an approximate LR test. We failed to reject this assumption at conventional levels across all LS items except for LS4 (SI Table 17), suggesting that ordinal logit model is an appropriate model for analysis.

LS item	**Chi2**	**Prob > chi2**
LS1	63.64	0.1984
LS2	59.56	0.3132
LS3	56.59	0.4155
LS4	87.09	0.0038
LS5	58.28	0.3558

SI Table 17: Approximate likelihood-ratio test of proportionality of odds across response categories.

1.1.5. Odds ratios and marginal effects

The discrete change effects were computed for *INITIATIVE* as a discrete variable.

	LS1 **In most ways my life is close to ideal**	**LS2** **The conditions of my life are excellent**	**LS3** **I am satisfied with my life**	**LS4** **So far I have gotten the important things I want in life**	**LS5** **If I could live my life over, I would change almost nothing**
ME (1)	-0.012***	-0.015***	-0.008***	-0.003	-0.018*
	(0.00)	(0.00)	(0.00)	(0.00)	(0.01)
ME (2)	-0.034***	-0.038***	-0.023***	-0.007	-0.019*
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
ME (3)	-0.045***	-0.041***	-0.038***	-0.009	-0.017*
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
ME (4)	-0.029**	-0.037***	-0.046***	-0.007	-0.007
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
ME (5)	0.031***	0.018***	-0.018**	-0.000	0.005**
	(0.01)	(0.01)	(0.01)	(0.00)	(0.00)
ME (6)	0.058***	0.066***	0.060***	0.013	0.029*
	(0.02)	(0.02)	(0.01)	(0.02)	(0.02)
ME (7)	0.031**	0.047***	0.071***	0.013	0.026
	(0.01)	(0.02)	(0.02)	(0.02)	(0.02)
INITIATIVE	*0.517****	*0.590****	*0.570****	*0.116*	*0.255**
	(0.17)	*(0.17)*	*(0.16)*	*(0.15)*	*(0.15)*
cut1	*-0.912*	*-1.040*	*-1.938****	*-1.783****	*-3.379****
	(1.39)	*(0.93)*	*(0.37)*	*(0.51)*	*(0.41)*
cut2	*0.642*	*0.470*	*-0.488*	*-0.413*	*-2.385****
	(1.39)	*(0.93)*	*(0.35)*	*(0.50)*	*(0.41)*
cut3	*1.741*	*1.397*	*0.579**	*0.619*	*-1.614****
	(1.39)	*(0.93)*	*(0.35)*	*(0.50)*	*(0.40)*
cut4	*2.763***	*2.472****	*1.561****	*1.492****	*-0.926***
	(1.39)	*(0.93)*	*(0.35)*	*(0.50)*	*(0.40)*
cut5	*4.157****	*3.703****	*2.736****	*2.505****	*-0.163*
	(1.39)	*(0.93)*	*(0.36)*	*(0.50)*	*(0.40)*
cut6	*5.718****	*5.268****	*4.267****	*4.028****	*1.234****
	(1.39)	*(0.94)*	*(0.36)*	*(0.51)*	*(0.40)*
Log pseudolikelihood	*-2757.87*	*-2771.35*	*-2712.07*	*-2800.49*	*-3024.02*
Pseudo R^2	*0.02*	*0.04*	*0.02*	*0.02*	*0.01*
Obs.	*1607*	*1606*	*1606*	*1606*	*1606*

SI Table 18: Marginal effects of initiative membership on the life satisfaction scale and OLOGIT results on the *INITIATIVE* coefficient and estimated cut points in italic. ME (1)-(7) refer to the average marginal effect of initiative membership. Significance level: *p<0.1, **p<0.05, ***p<0.01.

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Supplementary Information:

PAPER IV

Household energy footprints and the structural role of durable goods: A study of global developments from 1995 to 2011.

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Supplementary Information

Supplementary Discussion

Socio-demographics transitions and per capita energy footprints

Demographic shifts specially influence per capita footprints. Advanced economies typically have a stable socio-demographic composition, aged societies , and declining population and fertility rates (Lutz and KC, 2011; Lutz, Butz and KC, 2014). Steady and declining populations have proven to counteract economic growth, as might be the case for the advanced economies (Vásquez *et al.*, 2016) . The opposite phenomena governs transition economies, which are composed of relatively younger and growing populations; with larger segments striving for social mobility and decent living standards (Lutz and KC, 2011). The trends in countries in **Error! Reference source not found.** can be better understood in the light of the aforementioned phenomena.

Durables that save time and encourage productivity might also favor entrepreneurship and diversifying income sources, specially for the non-employed or homemakers (Pachauri and Rao, 2013). Poverty alleviation policies would consider the durables required to transform energy at the households: white goods, appliances, communication devices, lightning, heating and cooling, etc. (Rao and Min, 2017). Micro-data including socio-economic variables and physical units of durables would enlighten the implications for well-being and lifestyles of this research.

Durables in stock from a social metabolism perspective

A majority of stock changes in durables of advanced economies are presumably driven by conspicuous consumption, fashion cycles and planned obsolescence of personal devices (Ürge-

Vorsatz *et al.*, 2012; Grubler *et al.*, 2018), rather than actually by deploying basic household infrastructure (Waldman, 2003; Oguchi *et al.*, 2017; Teubler *et al.*, 2018). For these nations , the stock of basic durables is arguably in steady-state, and large portion of flows are destined to operate, serve, replace, upgrade and incrementally expand the current stock of basic household equipment (Vásquez *et al.*, 2016; Krausmann *et al.*, 2017, 2018).

Productivity and supply-side factors trends in durables

In 2000, personal consumption expenditures on durables exceeded $800 billion. In the manufacturing sector in the United States in the year 2000, durable goods production constituted 60 percent of aggregate production (Waldman, 2003). There has been virtually no change in the rate of productivity growth outside of the durable goods manufacturing sector which accounts for 12% of the US GDP. The productivity impacts of ICT investments have been limited to the computer and other durable goods manufacturing sector (Jalava and Pohjola, 2002).

Electrical and electronic goods are characterized by fast changing supply chains, rapid technological development, falling prices and high rate of exchanges for new technologies before the old ones fail as a subject of fashion (Teubler *et al.*, 2018).

Future Work: data availability and future requirements

A global, highly disaggregated, longitudinal, database on the consumption of durables that integrates information about physical units, prices (quality), life-cycle production, operational energy efficiency, and lifetimes (designed, perceived and effective) (Echegaray, 2016; Oguchi *et al.*, 2017) would enable testing and monitoring of policies for sustainable production and consumption (SDG12) and against planned obsolescence. A joint assessment of all durable-related goods would allow for detecting substitutability between products and services, as well as rebound effects of efforts towards servicing (leasing) (Intlekofer, Bras and Ferguson, 2010), circularity or shared economy. Ideally, such a database would be coupled with micro data to understand sub-national distributional effects and heterogeneity of socio-economic, well-being and time-use patterns (Jalas, 2002, 2008; Rao *et al.*, 2017).

Since we have national level economic data, we cannot compare previous implications for time use and household production (Ironmonger, 2000; Jalas, 2008). Durables are essentially productive capital; micro-data on durables and time could provide a picture of how people operate household equipment, putting skills and labor to self-provide valuable goods and services to household members. All of these aspects are currently absent in this work and despite using longitudinal data, we are not able to approximate a stock in a reasonable way.

We foresee such a database could be available in the following years with the verge of open and big data. There are several resources available such as LiVES lifetimes database (Oguchi *et al.*, 2010), Our World in Data (Oxford Martin Programme on Global Development, 2018), the UN MFA database (Krausmann *et al.*, 2017), and the global consumption database (The World Bank, 2018), among others.

Policies: Improved efficiency and longer lifetimes

Improving energy efficiency of durables is also part of the EU action plan (European Commission, 2008). Scenarios of low-energy demand for climate change mitigation estimates efficiency gains in household appliances of 50-67% by 2050 (Grubler *et al.*, 2018). Rapid efficiency improvements depend on accelerating the adoption of more efficient appliances, which in turn imply shorter lifetimes (Grubler *et al.*, 2018), in contradiction to the policy efforts towards SDG12 (European Commission, 2008; United Nations, 2016). While this might be feasible for small-scale, low-cost, granular technologies (laptops, phones), we show that the durables with the longest lifetimes (Teubler *et al.*, 2018), such as vehicles, big appliances and white goods, also demand the most operational and embodied energy.

Pushing for efficient appliances and longer-lived might be contradictory, as replacing current durables with better units relies on shorter lifetimes, as we discuss in the SI (Grubler *et al.*, 2018). Another underlying assumption behind these agendas is that durables are short-lived due to poor quality or planned obsolescence, however users' perception, not functionality, often drives shorter lifetimes (see SI) (Echegaray, 2016; Oguchi *et al.*, 2017). Previous studies detect that planned and perceived obsolescence of durable goods manifests as shorter lifespans (Oguchi *et al.*, 2017). This implies that a higher EF of durables does not strictly follows from more durables in stock, but might indicate a higher throughput (and replacement rate) of durable goods.

Sensitivity Analysis

From the 200 goods in our study, we find five that could fit more than one classification due to their level of aggregation. e.g. the industry "wholesale of household goods" includes machinery and chemicals. Table 1 shows the ambivalent goods and their alternative classification. Figure 1 shows the effect of using the alternative classification. We find that EF of durables would increase due to the large EF in "real estate services". Re-classifying wholesale and retail services, does not figure as an increase in "services outside home" due to their ten times smaller footprint in comparison to real estate services, which drives the sensitivity test. The EXIOBASE_ISIC sheet in the SD contains the detailed products and description linked included in our EXIOBASE product. This test is based on Net Energy, we expect the percent deviation to be comparable for final energy.

Table 1 | Ambivalent goods that might fit more than 1 category. The supplement. shows the current classification, the possible alternative classification as well lengthy definitions for each good.

Ambivalent Good	Current Classification	Alternative	Comment
Printed matter and recorded media	Durables	Consumables	Mix of audio, video and books with periodical publications
Wholesale trade and commission trade services*	Services to Durables	Services outside home	Mix of consumables and durables
Retail trade services*, repair services of personal and household goods	Services to Durables	Services outside home	Mix of consumables and durables
Post and telecommunication services	Services outside home	Services to Durables	Postal services occurs outside while telecommunication depends on durables
Real estate services	Services to Durables	Durables	Mostly operation of property, since construction has its own category, but contracted house repairs/construction might be captured there. E.g. living in apartment building
*except of motor vehicles and motorcycles;			

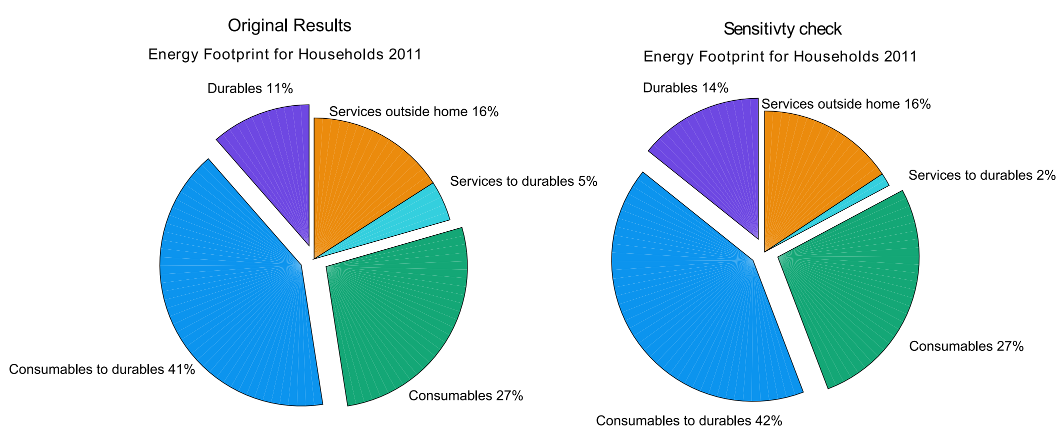

Figure 1 | Sensitivity test using alternative classification of ambivalent products based on Net Energy footprints. .

Shares of household consumption

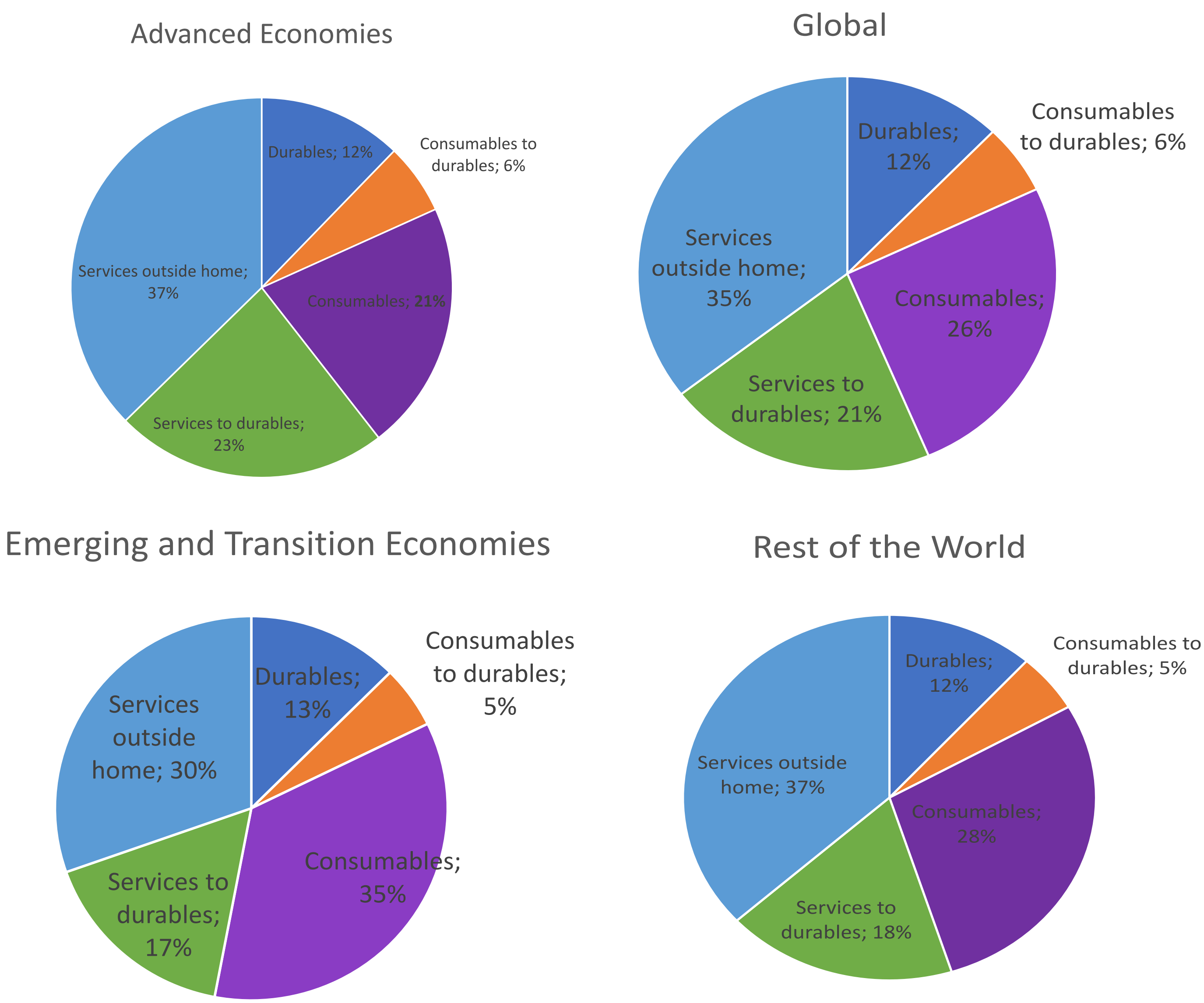

Figure 2 | Shares of household monetary demand by consumer goods and nation groups. EXIOBASE3 2011.

Correlation to estimate durable-related energy footprint

The graph shows a way to estimate durable-related energy given an assumed or measured EF of durables. Example: A 10% share of durable EF is divided by the slope of 0.6096 to calculate the ratio of durable/total durable-related EF. In this case durable/total durable-related EF = 0.16, assuming that 10% share is equal to 16 GJ/cap, solving for "total durable-related" in the ratio (Durable EF/ratio), we get 47 GJ/cap of durable-related EF.

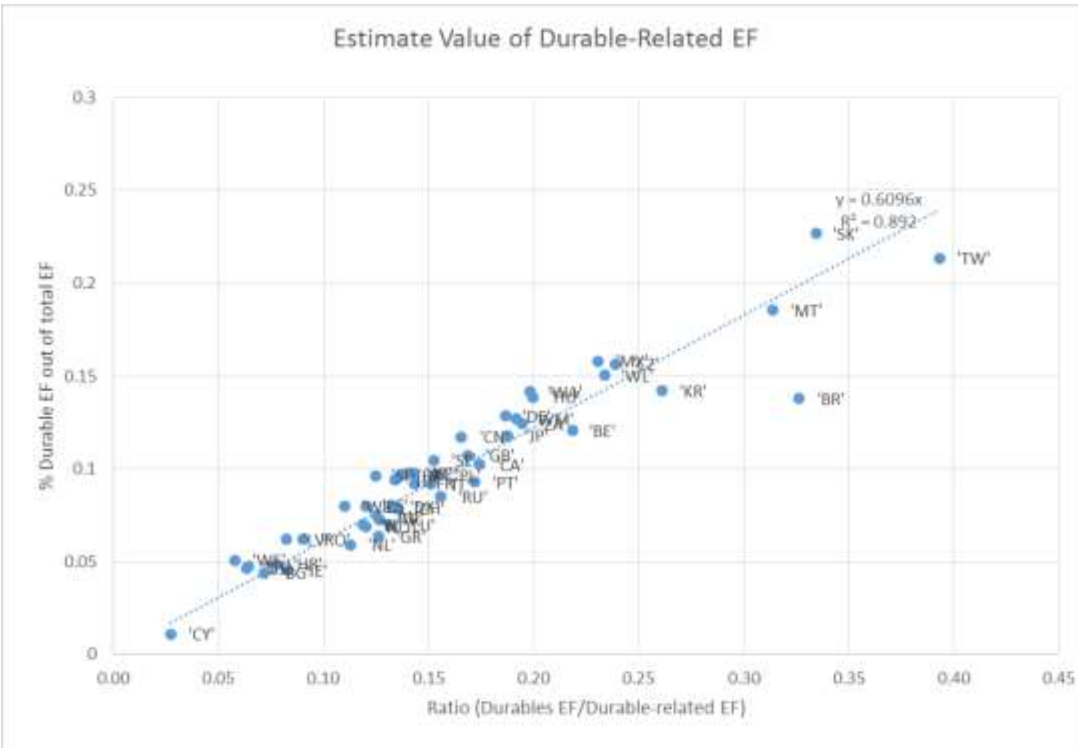

Figure 3 | Correlation to estimate durable-related energy footprint given a measured or assumed share of durable EF and EF. EXIOBASE 2011.

Net energy and carbon footprints

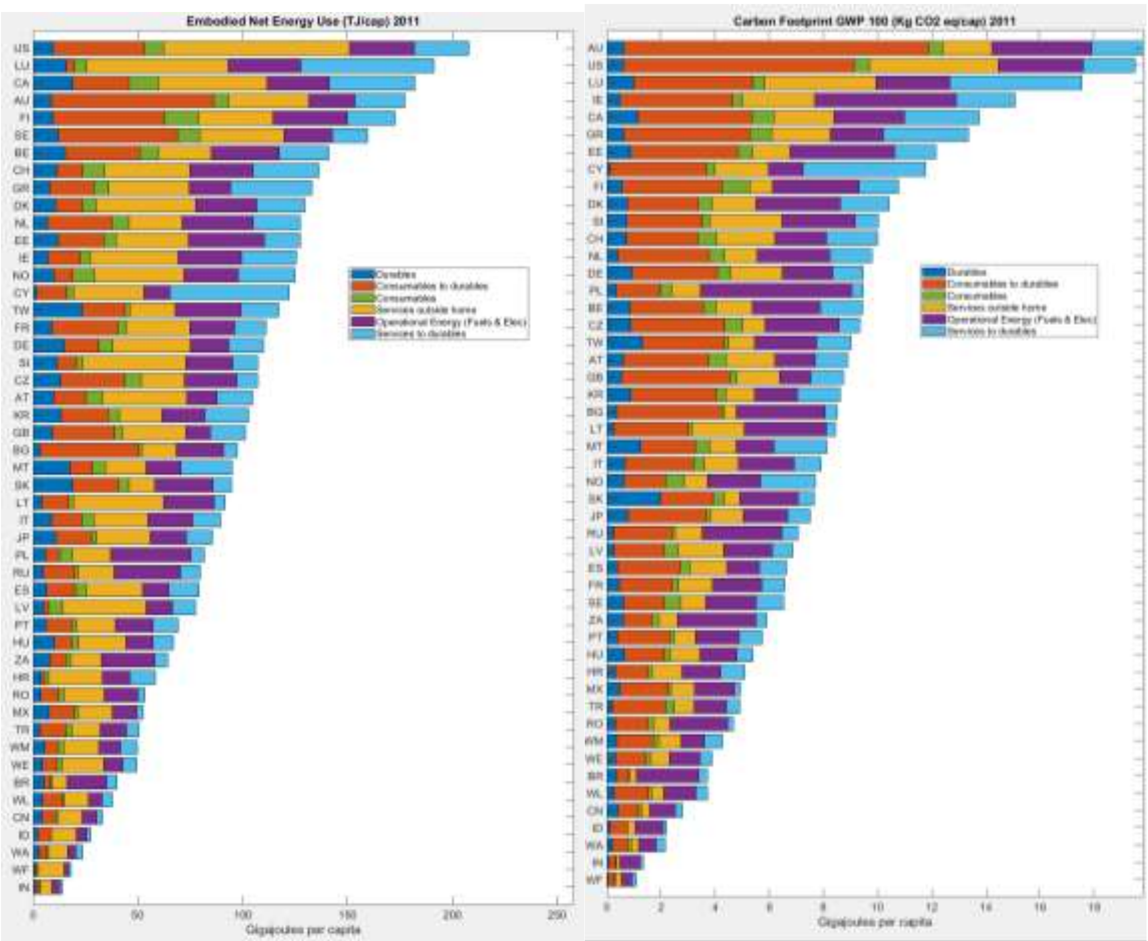

Figure 4 Net Energy and carbon footprints of households for different countries. EXIOBASE3 2011.

Supplementary Information
PAPER V

Food Security for an Aging and Heavier Population

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SUPPORTING INFORMATION

Food security for an ageing and heavier population

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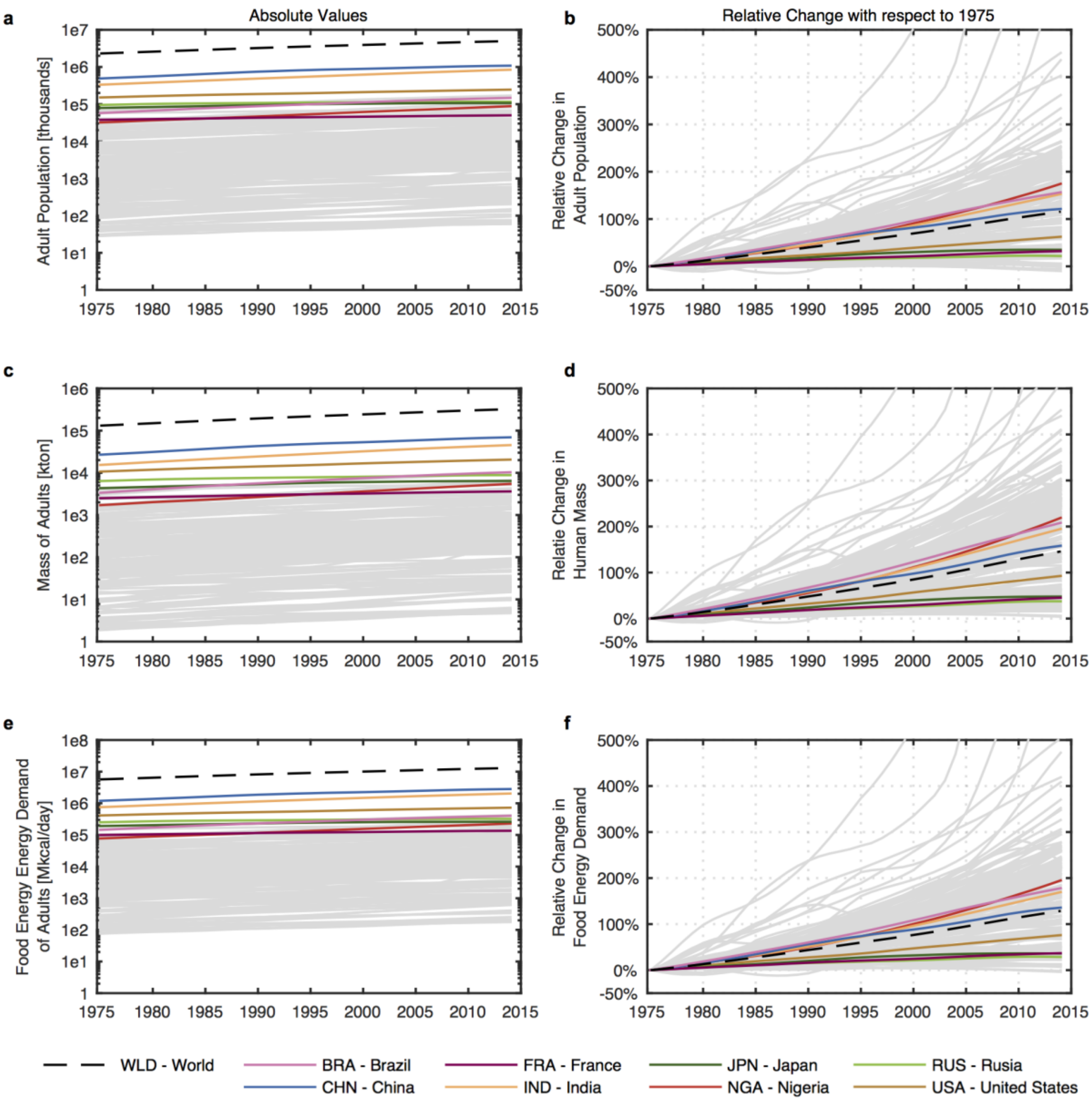

Figure S1. Absolute values (left - a,c,e) and relative changes (right - b,d,f) in total adults' population (a,b), mass (c,d) and food energy demand (e,f).

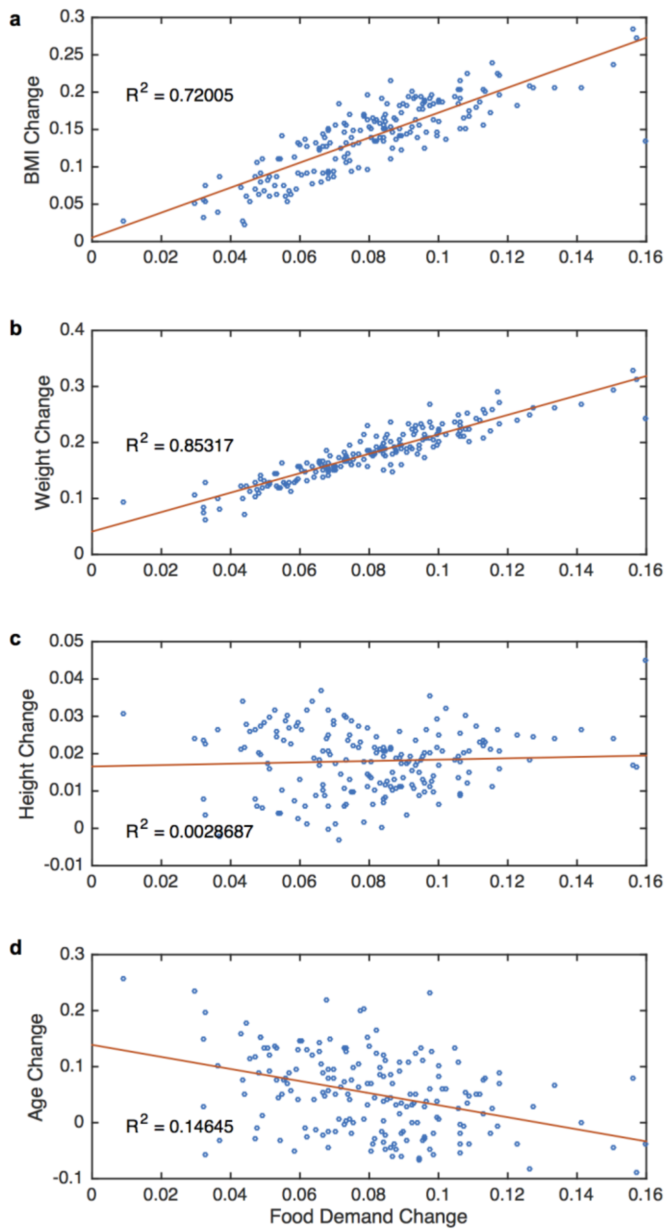

Figure S2. Linear correlation analysis between relative changes in body mass index (a), weight (b), height (c), and age (d) and relative changes in food energy demand. Changes in 2014 with respect to 1975 are studied. Each circle (blue) represents one country. The orange line is the linear fit with the R-squared displayed in the plot.

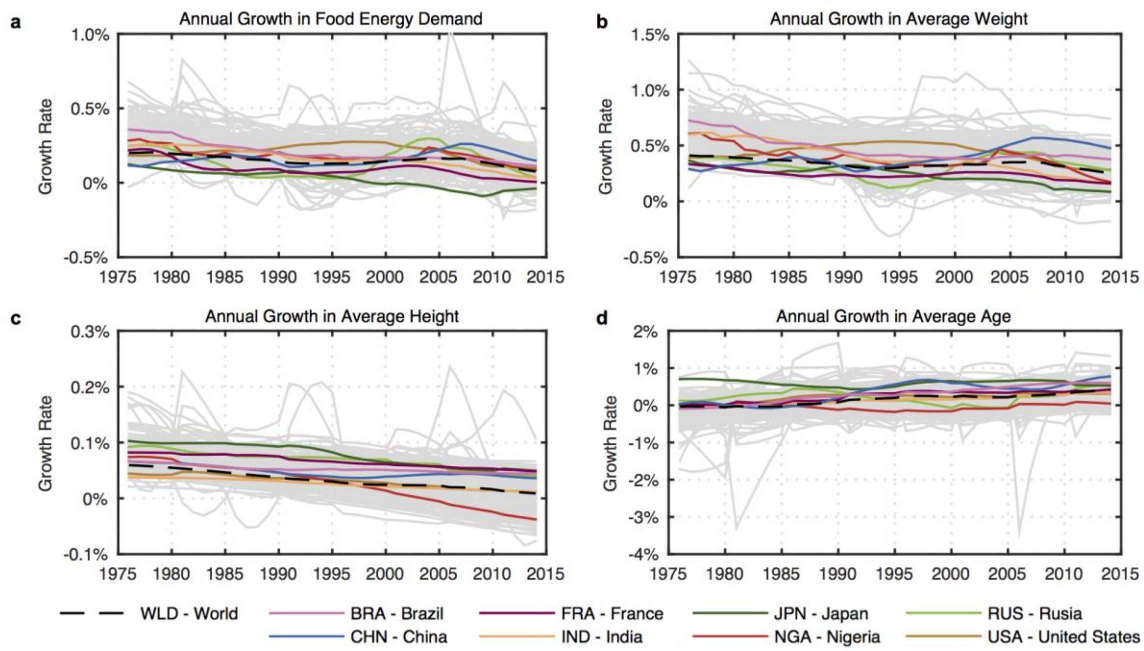

Figure S3. Growth rates in food energy demand (a), average weight (b), average height (c), and average age (d) of adults.

Demographic Modelling

Figure S4 presents a system definition for the study of the population stock and flows in given region. Six variables are considered: the Population Stock (P), the Population Stock Change (ΔP), Births (B), Deaths (D), Immigration (I) and Emigration (E).

The equations that explain each of the variables or the relationship among them are a generalization synthesized from different approaches found in literature [1–5]. Accordingly, this method does not intend to provide a complete description of all demographic phenomena, but instead to communicate the essentials of demographic modelling and to illustrate the use of a common mathematical language with socioeconomic metabolism modelling. Similarly, the terminology and notation greatly vary between authors in the field [4] , and thus here the most general terms have been selected.

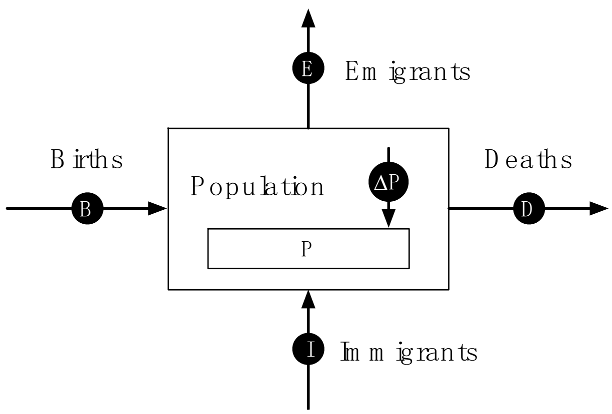

Figure S4 Classic demographic system definition. P and ΔP represent the population stock and its stock change respectively.

Balance Equation

In a region, the population (P) at the end of a given year "t" is the result of balancing the births (B), deaths (D), immigrants (I) and emigrants (E) of that year with population of the previous year, using the so-called demographic or population balancing equation [2,3,6] (Eq. 1).

$$P_t = P_{t-1} + B_t - D_t + I_t - E_t \qquad \text{(Eq. 1)}$$

Intrinsic Equations

Because the population is composed of individual of different sex "i" from different cohorts "c", it is also true that the population of a year "t" is the sum of the population of different sexes and cohorts (Eq. 2), and likewise the population change (Eq. 3).

$$P_t = \sum_i \sum_c P_{i,c,t} \qquad \text{(Eq. 2)}$$

$$\Delta P_t = \sum_i \sum_c \Delta P_{i,c,t} = \sum_i \sum_c (P_{i,c,t} - P_{i,c,t-1}) \qquad \text{(Eq. 3)}$$

Model Approach Equations

The total number of births in a year depends on the number of women "i=women" of each age and their age-specific fertility rate (FR) [4] (Eq. 4). This rate represents a woman's probability to have children, which vary along their life, and can be different across women of different cohorts.

$$B_t = \sum_c P_{i=women,c,t} \cdot FR_{c,t} \qquad \text{(Eq. 4)}$$

The probability of dying is also a function of the age of a person and can vary across cohorts along with changes in the life expectancy [2,4]. Therefore, deaths are estimated using a death or mortality rate (DR) (Eq. 5)

$$D_t = \sum_i \sum_c P_{i,c,t} \cdot DR_{i,c,t} \qquad \text{(Eq. 5)}$$

Finally, immigration and emigration can also be estimated from migration rates [1], in a similar fashion as for births and deaths.

Glossary

Definitions based on the Food and Agriculture Organization[7,8]

Anthropometry. Use of human body measurements to obtain information about nutritional status.

Body mass index (BMI). The ratio of weight-for-height measured as the weight in kilograms divided by the square of height in meters.

Birth cohort: A group of people born during a particular year

Bio-demography: is a new branch of human (classical) demography concerned with understanding the complementary biological and demographic determinants of and interactions between the birth and death processes that shape individuals, cohorts and populations.

Dietary energy requirement (DER). The amount of dietary energy required by an individual to maintain body functions, health and normal activity. .

Basal Metabolic Rate. Human energy requirements are computed by multiplying normative requirements for basic metabolic rate (BMR, expressed per kilogram of body mass) by the weight of a person given height, age and sex and then multiplied by a coefficient of physical activity level.

Kilocalorie (kcal). A unit of measurement of energy. One kilocalorie equals 1 000 calories. In the International System of Units (SI), the universal unit of energy is the joule (J). One kilocalorie = 4.184 kilojoules (kJ).

Food insecurity. A situation that exists when people lack secure access to sufficient amounts of safe and nutritious food for normal growth and development and an active and healthy life. It may be caused by the unavailability of food, insufficient purchasing power, inappropriate distribution or inadequate use of food at the household level. Food insecurity, poor conditions of health and sanitation and inappropriate care and feeding practices are the major causes of poor nutritional status. Food insecurity may be chronic, seasonal or transitory.

Food security. A situation that exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life. Based on this definition, four food security dimensions can be identified: food availability, economic and physical access to food, food utilization and stability over time.

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