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CASE REPORT

Lifestyle carbon footprints and changes in lifestyles to limit global warming to 1.5 °C, and ways forward for related research

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Abstract

This paper presents an approach for assessing lifestyle carbon footprints and lifestyle change options aimed at achieving the 1.5 °C climate goal and facilitating the transition to decarbonized lifestyles through stakeholder participatory research. Using data on Finland and Japan it shows potential impacts of reducing carbon footprints through changes in lifestyles for around 30 options covering food, housing, and mobility domains, in comparison with the 2030 and 2050 per-capita targets (2.5–3.2 tCO_2e by 2030; 0.7–1.4 tCO_2e by 2050). It discusses research opportunities for expanding the footprint-based quantitative analysis to incorporate subnational analysis, living lab, and scenario development aiming at advancing sustainability science on the transition to decarbonized lifestyles.

Keywords Carbon footprints · Sustainable lifestyles · Household consumption · Climate change mitigation · Paris agreement

Introduction

Given the fact that unsustainable lifestyles, which are rooted in household consumption, have a key bearing on total global greenhouse gas (GHG) emissions, they are being increasingly focused on as a key to unlocking actions that can be taken to mitigate climate change. This central message is echoed in the Intergovernmental Panel on Climate Change (IPCC)'s Special Report on the impacts of global warming of 1.5-degrees (IPCC 2018), as well as the conclusion of the United Nations Environment Programme (UNEP) Emissions Gap Report 2020 which devotes a chapter to low-carbon lifestyles (UNEP 2020). Further, the upcoming IPCC sixth assessment report is expected to highlight demand and social aspects of mitigation (Creutzig et al. 2018). At the country level, national and regional governments now also incorporate lifestyle and behavior changes into their long-term strategies, in parallel with technological changes. Transformation to a net-zero economy is "not just about technologies (…but) about people and their daily lives" and "lifestyle choices can make a real difference, while improving quality of life" (European Commission 2018) and "shifting the way of life (…) provides a major impact directly and indirectly on climate change" (Government of Japan 2019).

In terms of research on lifestyle changes and climate change mitigation, the body of literature has grown but is still limited. For example, emission pathways based on the integrated assessment models (IAMs) incorporate various aspects of lifestyle changes; however, these need to be developed to more comprehensively explore the impacts of indirect emissions through the lifecycle of goods and services (van den Berg et al. 2019; Saujot et al. 2021). Studies in the field of industrial ecology using environmentally extended

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input–output analysis (EEIOA) and life cycle assessment (LCA) have revealed characteristics of current household carbon footprints and examined those linked with high-carbon lifestyles (Hertwich 2005; Tukker et al. 2010). GHG emissions resulting from household consumption comprise 58–72% of total global emissions (Ivanova et al. 2016; Hertwich and Peters 2009). These carbon footprints consist of both direct emissions, such as the use of fossil fuels at home and for driving, and indirect emissions resulting from the use of goods and services by households—which can be even higher than the direct ones (Hirano et al. 2016). Recent developments in this field include attempts to quantify mitigation impacts from a variety of demand-side options related to food, housing, and mobility (Jones and Kammen 2011; Schanes et al. 2016; Bjelle et al. 2018; Wood et al. 2018; Ivanova et al. 2020; Moran et al. 2020). Despite the rising number of such studies, however, most focus only on the potentials based on individual demand-side options and offer no concrete scenarios in the form of the aggregated impacts from lifestyle changes required to close the gaps between currently prevalent heavy carbon footprints and the climate targets. Building on these existing approaches, the present study proposes a consumption-based target for lifestyle carbon footprints and also explores the extents needed to change lifestyles to meet the 1.5 °C climate target of the Paris Agreement.

This paper proposes an approach for assessing lifestyle carbon footprints and lifestyle changes aimed at limiting global warming to 1.5 °C and facilitating the transition to decarbonized lifestyles through participatory research. After introducing per-capita targets of lifestyle carbon footprints, it provides a hotspot analysis of current lifestyles and mitigation impacts from individual and multiple lifestyle change options, focusing on the case studies of Finland and Japan. The quantitative results discussed are based on the key findings from phase I of the "1.5-Degree Lifestyles" project, an international research project on decarbonizing lifestyles, and its technical report (IGES et al. 2019). Building up to the quantitative analysis, it discusses research opportunities including subnational analysis, living lab, and scenario analysis that could be followed up on to facilitate lifestyle changes that can be taken aimed at decarbonization.

Consumption-based per-capita targets corresponding to the 1.5 °C climate goal

This section explains the different types of targets and their relevance. Typically, climate change targets have been discussed in terms of territorial emissions such as at the country level (Climate Analytics and NewClimate Institute 2020), but such accounting cannot comprehensively capture the impacts of consumption activities through indirect emissions in supply chains occurring outside of the territory being studied. On the other hand, consumption-based carbon footprint accounting is useful for devising policies that avoid leakage of emissions beyond territorial borders—an approach empowering governments, companies, and consumers to shape low-carbon actions at the global, country, city, and household levels (Peters 2010).

Further, most existing targets are proposed at the aggregated level, such as global and country totals, but in the context of promoting lifestyle changes, aggregated territorial-based targets may not be explicitly relevant to households and local stakeholders, since such targets are not directly linked to people's daily lifestyles or fail to account for the indirect emissions resulting from consumption. Therefore, consumption-based per-capita targets can facilitate actions to decarbonize people's lifestyles, and can also reveal the gaps between predominant lifestyles and levels of decarbonization required to meet the targets.

In this study, we define "lifestyle carbon footprints" as the sum of direct and indirect GHG emissions induced from household consumption, excluding government expenditure and capital investment. In relation to the planetary boundaries (Rockstrom 2009; Steffen et al. 2015), few studies have attempted to downscale climate change boundaries into per-capita targets (Nykvist et al. 2013; Dao et al. 2015). Further, these targets are static and fail to account for the gradual reduction in carbon emissions anticipated to take place by the second half of the twenty-first century, as suggested by the major mitigation pathways aligned with the climate goals (UNEP 2020). For these reasons, the present study established consumption-based per-capita targets of lifestyle carbon footprints assuming the gradual decrease of carbon budgets to the second half of the century.

The per-capita lifestyle carbon footprint targets proposed below are based on a review of existing emission pathways, projections of global population (United Nations 2017), and share of carbon footprints of household consumption in total footprints (Hertwich and Peters 2009). As shown in Fig. 1, using the identified representative pathways towards the 1.5 °C Paris Agreement goal, and considering either limited or intensive use of negative emission technologies (van Vuuren et al. 2018; Ranger et al. 2012; Rockström et al. 2017), the upper and lower annual targets of per-capita lifestyle carbon footprints are: 2.5–3.2 tCO_2e in 2030, 1.4–2.2 tCO_2e in 2040, and 0.7–1.4 tCO_2e in 2050. It should be noted that, to explicitly focus on the parts related to lifestyles of citizens, these targets do not include footprints resulting from government expenditure and capital investment. However, accounting for such factors in allocating footprints could be taken up in future research, as they are not only factors related to satisfying the needs of a country's citizens but also those of future generations, as well as its exports.

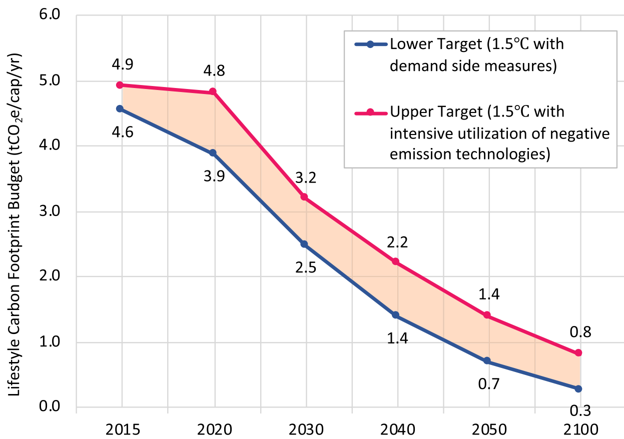


Fig. 1 Lower and upper targets of per-capita lifestyle carbon footprints in relation to meeting the 1.5 °C climate goal. Per-capita targets of carbon footprints from household consumption, excluding government expenditure and capital investment. Red and blue target figures refer to pathways compatible with the 1.5 °C target; the lower (blue) target emphasising demand-side measures and no intensive use of negative emission technologies, and the upper (red) with intensive use of negative emission technologies. Source: developed by authors to indicate only 1.5 °C target ranges based on data from IGES et al. (2019)

In the above, the lower and higher targets are figures based, respectively, on pathways emphasising demand-side measures without and with intensive use of negative emission technologies. In terms of the carbon budget, the latter is close to a 2 °C target with extensive use of negative emission technologies.

Assessing hotspots of lifestyle carbon footprints and comparing them with targets

Here, we explain the approach for assessing lifestyle carbon footprints, present the results of estimations, the gaps between current lifestyle carbon footprints and the targets, and the hotspot areas of lifestyle carbon footprints.

Assessing lifestyle carbon footprints through consideration of different consumption domains and components can help to identify underlying problems and potential solutions. There are two basic approaches for estimating carbon footprints. One, used in most existing studies on carbon footprints related to household consumption, is monetary-based estimation (Hertwich 2005; Tukker et al. 2010; Ivanova et al. 2016). The other focuses on lifestyles based on physical amounts of consumption, for which limited studies exist (Barrett et al. 2002; Nissinen et al. 2007; Girod et al. 2010; Moore et al. 2013; Lettenmeier 2018). In our study, we mainly used estimation based on physical amounts of consumption, since it can more accurately model substitutions between different consumption items—such as transportation modes, energy sources, and food ingredients. This approach also facilitates a better understanding of the consumption patterns of citizens, since it examines carbon footprint hotspots on the basis of both physical consumption amounts and carbon intensities.

Using the physical-amount approach, we examined carbon footprints and characteristics of consumer lifestyles focusing on food, mobility, and housing, and examined the amounts quantified based on actual physical amounts of consumption. The quantities estimated were based on figures for mobility distance in passenger-km, food consumption in kg, and energy consumption in kWh. For the other domains such as leisure, consumer goods, and services we used monetary-based estimation, to ensure we had a fuller picture, or overview of household consumption.

We estimated carbon footprints of average consumers in five target countries, including Finland and Japan, for nutrition, housing, and mobility domains based on the collected national and other official statistics, such as nutrition intake and food supply, transport and fuel consumption, housing and water supply, and energy statistics. To estimate carbon footprints for each product and service, we used carbon intensity data obtained from life cycle inventory databases, which are widely used and provide extensive coverage of items, such as Ecoinvent (Wernet et al. 2016), as well as additional data on carbon footprints in other domains from input–output models such as ENVIMAT (Seppälä et al. 2009) and GLIO (Nansai et al. 2012). These carbon footprints and physical consumption amounts were aggregated into several components per domain to enable comparison between the target countries and quantification of the impacts from lifestyle changes. More details on the data sources are available in the technical report (IGES et al. 2019).

Assessing lifestyle carbon footprints and gaps with the targets

Results of the analysis revealed significant gaps between current lifestyle carbon footprints and the 2030–2050 targets. Figure 2 shows the estimated lifestyle carbon footprints of average consumers in five countries, encompassing all aspects of household consumption—nutrition, housing, mobility, consumer goods, leisure, and services—in comparison with the lower and upper targets. The results clearly point to the need for drastic and rapid reductions in lifestyle carbon footprints of 60–80% by 2030 and 80–90% by 2050 in developed countries (Finland and Japan) and up to 40% in 2030 and at least 20% to over 80% in 2050 in developing countries (China, Brazil, and India).

Comparing hotspots of lifestyle carbon footprints with the targets

The gaps between the currently dominant lifestyles and the targets for 2030 and 2050 in each domain highlight the need for drastic changes in both consumption patterns and carbon intensities. The estimated lifestyle carbon footprints and physical consumption patterns were visualized as skyline charts to examine the hotspots, and comparisons were made with the per-capita targets introduced in the previous section (Fig. 3). For each colored block (rectangle) in the figure, its area represents the carbon footprint of the item, the width refers to consumption amount, and the height shows carbon intensity. The figure also shows current and indicative target carbon footprints, with dotted lines showing average intensities across components. Here, the allocation of target carbon footprints between carbon intensity and consumption amounts as well as between domains is only indicative, as different forms of allocations are possible. Nevertheless, even an indicative target can provide useful insights on the extent and coverage of the changes required to meet the related target.

These visualizations enable an intuitive understanding of the hotspots of lifestyle carbon footprints based on physical consumption, either due to large carbon footprint (size of the area) or high-carbon intensity (large height)—for example, consumption of meat, energy from fossil fuels, car-driving, and flights. Moreover, comparison with targets in each domain can deepen our understanding of the levels and types of changes in lifestyles and provisioning systems that will be required. To illustrate, in the mobility domain, rapid reduction of both transport distance and intensity may be needed to comply with the 1.5 °C target (comparing the size of black, pink, and light blue dotted line boxes). Apart from the larger blocks (height of gray and red blocks) shown in this domain, it is noteworthy that the carbon intensity of even current bus services (height of dark blue block in comparison with pink/light blue dotted line target boxes) makes them not compliant with the targets in the future.

These points illustrate the need for a transition in consumer lifestyles to comply with the climate target. Further, such transition would need to be supported by innovative provisioning systems.

Carbon footprint reduction potentials from lifestyle changes: individual options and aggregated impacts

Listing the potential lifestyle change options and understanding their footprint reduction potentials is useful for examining the effectiveness of different measures. In this study, incorporating a framework based on existing literature (Nelldal and Andersson 2012; Figge et al. 2014; Akenji et al. 2016), we classified the major approaches used for reducing carbon footprint by lifestyle changes into three basic types: (1) Absolute reduction: reducing the amount of physical consumption of goods and services; (2) Efficiency improvement: reducing the emissions by introducing alternative lower-carbon technologies, while keeping the same mode of consumption and amount; and (3) Modal shift: substitution of a consumption mode by another less carbon-intensive mode, while keeping the same amount of functional demand.

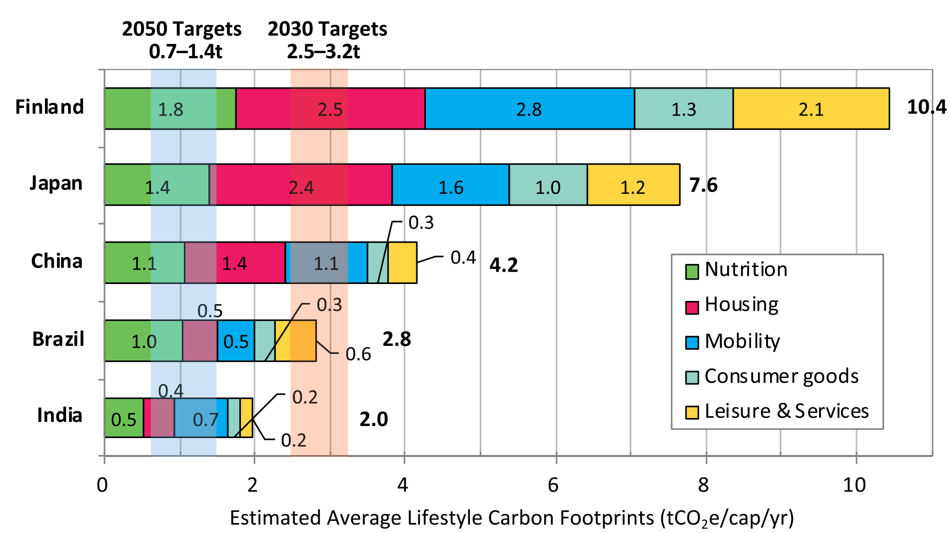


Fig. 2 Gaps between current lifestyle carbon footprints of average citizens in countries and 2030–2050 targets. Source: authors based on data from IGES et al. (2019)

Mitigation impacts from lifestyle change options

Here, we show how changes in lifestyle can reduce carbon footprints for the two case countries (Finland and Japan) with maximum mitigation potential. To do this, we first identified the lifestyle change options that would have the most impact by literature review, then quantified around 30 options per country. Calculations were made based on the three approaches proposed above and the lifestyle carbon footprint and physical amounts of consumption estimated in this study. Absolute reduction can be modeled by reducing physical consumption amounts, and efficiency improvements can be reflected by reducing carbon intensities in the dataset. Modal shifts can be quantified by shifting amounts of consumption of particular items to another item, as each has a different carbon intensity.

We focused on quantifying the maximum potential of footprint reduction assuming full adoption (100% adoption rate) of an option—for example, commuting without any car or always eating vegetarian meals—but also show results for partial adoption of options. This is because in the real world, households are more likely to only make partial use of commuting by bicycle or vegetarian meals, or only a part of the population might adopt these options. Figures for partial adoption were calculated by multiplying full implementation impacts by the adoption rate.

Figure 4 shows the lifestyle change options identified. The most effective options include private travel without a car, shifting to renewable electricity, electric cars, vegetarian diets, and vehicle efficiency improvement (potential of each option if fully implemented: 500 kg to over 1500 kg CO_2e per capita on average). Other effective options include ridesharing, living close to the workplace, temperature control using heat pumps, commuting without a car, use of dairy product alternatives, low-carbon proteins, and living in smaller spaces (250–500 kg CO_2e per capita).

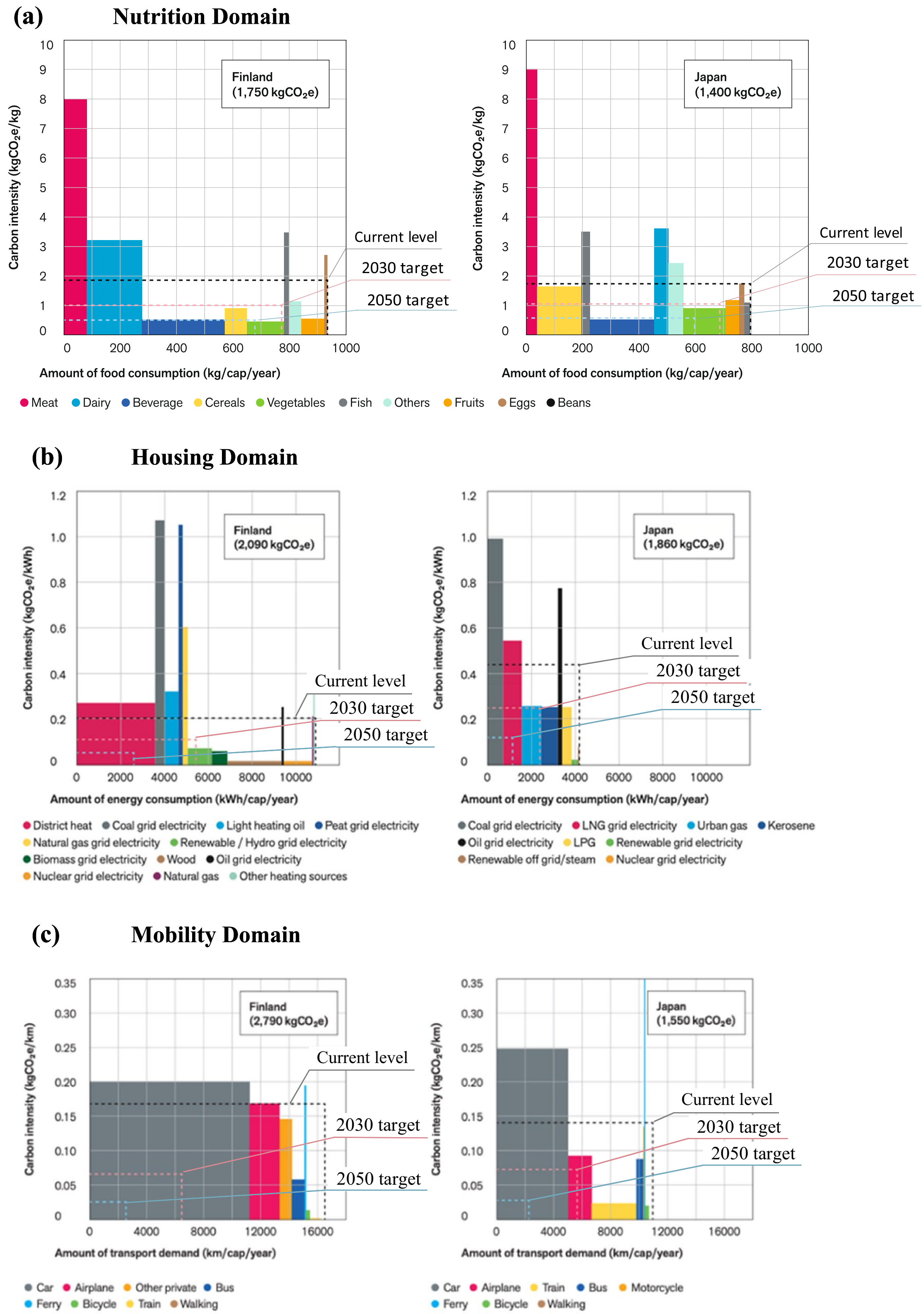
These results also highlight the importance of covering all three approaches discussed in this paper: absolute reduction, modal shift, and efficiency improvements. For example, many of the most impactful options with mitigation potentials over 500 kg CO_2e per-capita adopt the modal shift approach, such as shifting from cars to public transport, from conventional to renewable energy, from gasoline to electric cars, and from meat-rich to vegetarian diets, but also on the efficiency improvement approach, such as using efficient vehicles and ride sharing. Absolute reduction options are also prominent among the effective options identified, such as reducing mobility distance, living space, and hot water consumption.

As illustrated in the figure, the mitigation potentials differ among the case countries. This implies that the effectiveness of lifestyle change options depends on each context, such as differences due to actual physical consumption patterns, e.g., car driving, meat and dairy product consumption, energy consumption, and grid electricity mix. There are also background reasons, such as different structures in provision, infrastructure, and habits of consumers. Therefore, options such as car-free travel and dietary shift have larger mitigation potentials in Finland, whereas other options such as renewable electricity are more effective in Japan.

Aggregated mitigation impacts from lifestyle changes

To better understand the level and types of demand-side actions needed to meet the 1.5 °C climate goal, we investigated lifestyle changes beyond the individual option of lifestyle changes, through quantifying the aggregate mitigation potentials from multiple options covering all the consumption domains of food, housing, mobility, goods, leisure, and services. Adding up the impacts from more than one lifestyle change option does not produce accurate aggregate figures due to areas of synergy and overlap. Therefore, aggregated impacts from multiple lifestyle change options were quantified by considering the overlaps and synergies. As an initial attempt to examine the level of required changes, we made a basic assumption that all selected options were adopted at the same rate. The analysis results (Fig. 5) revealed that 65–75% adoption of approximately 30 quantified options in combination with 65–75% reduction of footprints in goods, leisure, and services by 2030 would be needed for both countries to comply with the upper to lower targets of 2030 (2.5–3.2 tCO_2e).

This means that ambitious adaption of lifestyle change options can contribute to reducing lifestyle carbon footprints towards the targets of the Paris Agreement. However, the level and coverage of required changes is both high and broad due to the proximity of year 2030. In view of the 2050 targets, the analysis also concludes that even full implementation of these options with 90% reduction of footprints in goods, leisure, and services is not sufficient to meet the 2050 lower target (0.7 tCO_2e). This implies that much broader-ranging lifestyle change options and systemic changes, including large-scale behavioral changes combined with huge innovations in provisioning systems may be needed to comply with the 1.5 °C climate goal. These findings on aggregated mitigation impacts from the combination of multiple lifestyle change options underscore the need for ambitious uptake of currently available options and additional new decarbonization options, as well as structural changes in consumption habits and provisioning systems.



(a) Nutrition Domain
Finland (1,750 kgCO₂e)
Japan (1,400 kgCO₂e)
Current level
2030 target
2050 target
Carbon intensity (kgCO₂e/kg)
Amount of food consumption (kg/cap/year)
Meat
Dairy
Beverage
Cereals
Vegetables
Fish
Others
Fruits
Eggs
Beans
(b) Housing Domain
Finland (2,090 kgCO₂e)
Japan (1,860 kgCO₂e)
Current level
2030 target
2050 target
Carbon intensity (kgCO₂e/kWh)
Amount of energy consumption (kWh/cap/year)
District heat
Coal grid electricity
Light heating oil
Peat grid electricity
Natural gas grid electricity
Renewable / Hydro grid electricity
Biomass grid electricity
Wood
Oil grid electricity
Nuclear grid electricity
Natural gas
Other heating sources
Coal grid electricity
LNG grid electricity
Urban gas
Kerosene
Oil grid electricity
LPG
Renewable grid electricity
Renewable off grid/steam
Nuclear grid electricity
(c) Mobility Domain
Finland (2,790 kgCO₂e)
Japan (1,550 kgCO₂e)
Current level
2030 target
2050 target
Carbon intensity (kgCO₂e/km)
Amount of transport demand (km/cap/year)
Car
Airplane
Other private
Bus
Ferry
Bicycle
Train
Walking
Car
Airplane
Train
Bus
Motorcycle
Ferry
Bicycle
Walking

◂**Fig. 3** Hotspot analysis of average carbon footprints and consumer lifestyles based on physical amounts of consumption in two case countries (Finland and Japan). *X*-axis, *Y*-axis, and size of the area of each block equate to physical amount of consumption, carbon intensity, and carbon footprint, respectively; black, pink, and light blue dotted lines represent current level, 2030 target, and 2050 target (1.5 °C, lower target) footprints, respectively. Source: modified by authors based on IGES et al. (2019)

Research opportunities to progress sustainability science on decarbonized lifestyles

Through the combination of per-capita consumption-based target setting, analysis of lifestyle carbon footprints, and quantification of mitigation impacts from individual and multiple lifestyle change options, the present study identifies challenges and opportunities towards decarbonized lifestyles. The quantitative analysis proposed above represents only an initial step, and further research is needed in this field. Recognizing that there are gaps between decarbonization targets and current lifestyle carbon footprints, there is a need for exploring how to fill them, through incorporating lifestyle changes. The analysis of lifestyle carbon footprints in this paper identified means to reduce GHG emissions derived from consumer lifestyles—absolute reduction, modal shift, and efficiency improvement. In terms of implementation, the area to be focused on going forwards is how to capitalize on these means to support citizens, communities, governments, businesses, and other stakeholders in transforming lifestyles and contexts of living. This can be approached from three perspectives: clarifying the impacts from lifestyle changes and the gaps with the target, envisioning possible future based on consumption-based scenarios and roadmaps, and facilitating lifestyle changes in real-life settings. To date, from the footprint perspective, only a few existing studies adopt the participatory approach, through stakeholder workshops (Leppänen et al. 2012; Vita et al. 2019). This section extends the footprint-based quantitative analysis to incorporate these perspectives through subnational analysis on carbon footprints and lifestyle changes, integration with living lab approaches, and consumption-based scenario development.

Subnational analysis of lifestyle carbon footprints and lifestyle changes

One opportunity as an area of study is analysis of lifestyle carbon footprints and lifestyle changes at the subnational level. The availability of data related to household consumption is growing—not only in the conventional format of aggregated statistics of household consumptions at both country- and city-level but also covering different aspects of household consumption, including survey microdata of individual responses to surveys. As illustrated in this paper, quantifying mitigation potentials from lifestyle changes help to understand the effectiveness and potential contributions of lifestyle changes to the climate goals. However, to date, most studies on the quantification of carbon footprint reduction focus on countries or regions (Jones and Kammen 2011; Schanes et al. 2016; Bjelle et al. 2018; Wood et al. 2018; Ivanova et al. 2020; Moran et al. 2020), with only a few exceptions (Hersey et al. 2009; Dubois et al. 2019). Considering the pivotal roles of cities in activating sustainable lifestyles and decarbonized societies (Peters 2010; Wright et al. 2011; Bailey et al. 2019), the assessment of lifestyle carbon footprints proposed in this paper could be extended to subnational units such as cities and local communities.

A similar analysis can also be extended to quantify mitigation potentials from lifestyle changes in different consumer segments using survey microdata. Previous research based on survey microdata covering carbon footprints of households or consumer segments has revealed that they vary widely, even within-country, by from 3 to 10 times (Weber and Matthews 2008; Froemelt et al. 2018; Koide et al. 2019). This analysis approach is especially relevant considering the growing awareness of the inequalities, in terms of carbon footprints, between consumer and income segments globally and within each country, which underscores the urgency of addressing the emissions and footprints of high-carbon population segments (Kartha et al. 2020; Ivanova and Wood 2020; UNEP 2020). The segmentation method in existing studies can be combined with the approach proposed in this paper to investigate the impacts of a transition in lifestyles of different consumer segments. Such analysis can identify mitigation potentials in terms of high-carbon activities and high-carbon population segments, which are both useful when considering the equitability and effectiveness of mitigation actions.

Integration of lifestyle carbon footprint analysis with living lab approaches

There is a need to examine the feasibility of lifestyle changes, levels of potential acceptance by citizens, and necessary supporting measures and policy actions, as well as assess the impacts from a carbon footprint perspective. A deeper and more realistic understanding of lifestyle changes can be obtained from the living labs approach. 'Living labs' refers to an open innovation platform with real-life environments to address societal challenges through the collaboration of various stakeholders (Hossain et al. 2019). Application of living labs to studies of sustainability can investigate various aspects of sustainable

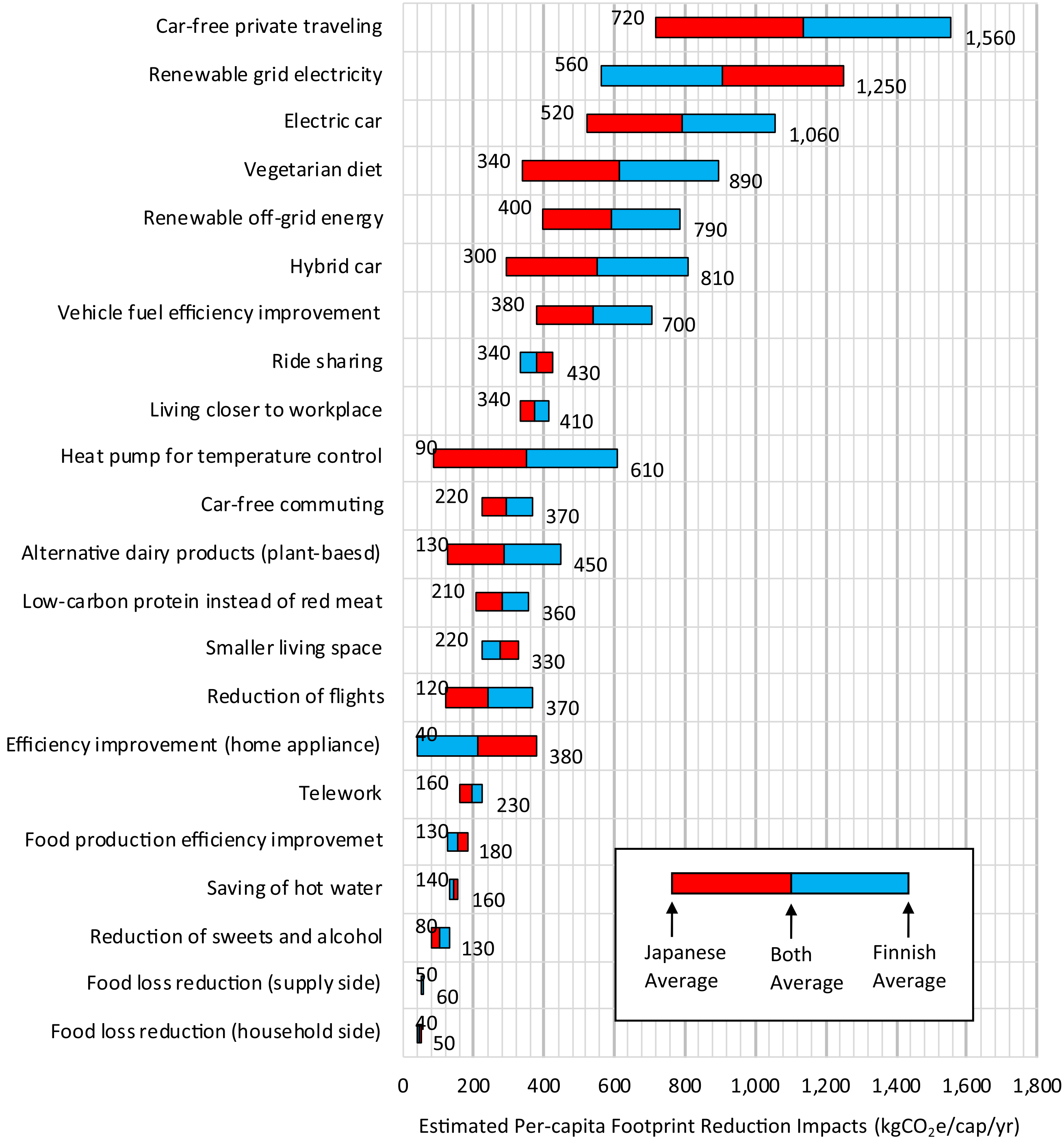


Fig. 4 Mitigation potentials from lifestyle change options in two case countries (Finland and Japan). Figures at left and right ends of each box show average mitigation potential of each option in each country if fully implemented; middle line represents average of both countries. Note that overlaps or synergies between lifestyle change options are not considered in this figure. Source: developed by authors based on data from IGES et al. (2019)

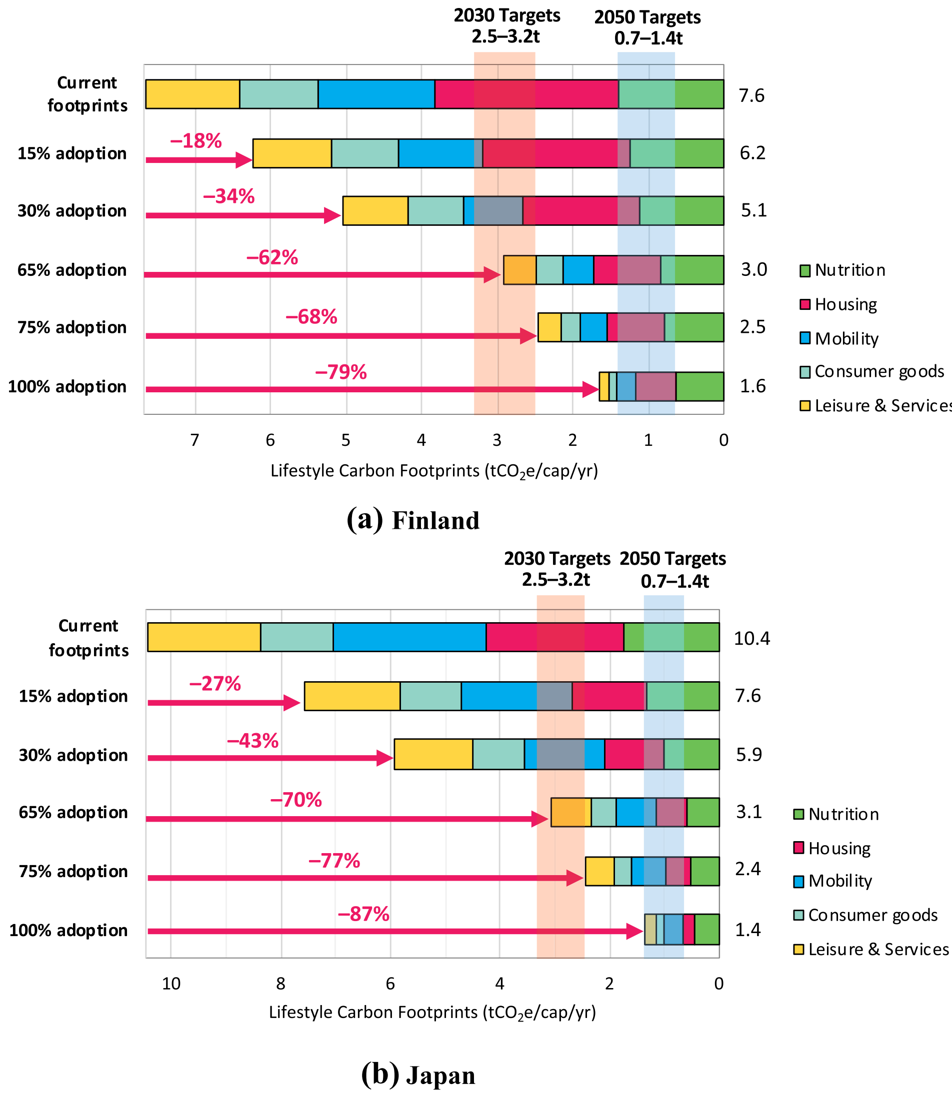


Fig. 5 Aggregated impacts from lifestyle change options and comparison with 1.5 °C targets (Finland and Japan). The bar chart indicates current and scenario lifestyle carbon footprints with corresponding adoption rates of lifestyle change options. Arrows represent total reduction impacts. At 100% adoption, the assumed reduction in carbon footprints of consumer goods, leisure and services is 90%. Source: developed by authors based on data from IGES et al. (2019)

living, including quality of life, environmental impacts, and the implications of daily routines (van Timmeren and Keyson 2017), through focusing on behaviors and experiences in real-life settings with mixed-method research (Herrera 2017). Living labs may contribute to generating useful applied knowledge and inspiring rapid transformations in society and technology, creating not only direct impacts at the niche level but also indirect impacts through adjustment of policies and provision structures, as well as diffuse impacts on cultural and normative values of societies (Schliwa et al. 2015).

The living labs approach has numerous applications in low-carbon urban development (Voytenko et al. 2016) and daily practices related to domains of lifestyles such as food, energy, building, work, and product use (von Geibler et al. 2014; Davies and Doyle 2015; Devaney and Davies 2017; Kivimaa et al. 2017; Jensen et al. 2018). However, a living lab approach that seeks to obtain information on sustainable actions based on energy use or direct GHG emissions cannot fully account for the climate change impacts of daily living from the consumption-based perspective. To date, a limited number of studies have used the living labs approach to focus on the life cycle impacts of lifestyles, such as using carbon and material footprints (Hedenus 2011; Laakso and Lettenmeier 2016; Lahtinen et al. 2020; Greiff et al. 2017). Although not labeled as a living lab approach, the life cycle approach has also been combined with small-scale experiments to identify effective interventions (Wynes et al. 2018). One possible approach could involve use of a footprint calculator as well as analysis of lifestyle changes, as illustrated by some examples of online platforms for personal carbon footprint estimation and target pledges (West et al. 2016; Commission for Sustainable Development 2020). These experimentations with real-life settings can be combined with the methodology proposed in this paper to better comprehend the practicality as well as necessity of certain actions, to facilitate impactful lifestyle changes.

Developing consumption-based mitigation scenarios and roadmaps incorporating lifestyle changes

As this paper shows, examining aggregated impacts by combining multiple lifestyle change options helps us understand the lifestyle changes that are needed to meet the climate goals. Desirable outcomes in the future can be approached through development of future scenarios and roadmaps incorporating carbon footprints and lifestyle changes. Aiming towards decarbonized lifestyles, such efforts could incorporate three elements: (1) consumption-based carbon footprints and mitigation potentials from lifestyle changes explicitly linked to the decarbonization target, (2) participatory process involving citizens and stakeholders, and (3) roadmaps with supporting measures through policy and stakeholder actions, as explained below.

First, scenario analysis can be based on consumption-based carbon footprints and explicitly indicate pathways to the decarbonization target. To date, a number of low-carbon scenarios based on direct emissions incorporating the backcasting approach have been proposed (Hughes and Strachan 2010). However, these scenarios cannot fully account for the indirect impacts from consumption activities related to lifestyles, due to the relatively large indirect emissions. Conversely, from a consumption-based perspective, some studies quantified impacts from multiple demand-side options (Vita et al. 2019; Moran et al. 2020), but these studies do not focus on the gap with the decarbonization targets. Only a limited number of scenarios of future lifestyles have been developed that comprehensively consider life cycle impacts and the gaps with the target levels (Girod et al. 2014; Lettenmeier et al. 2014; Impiö et al. 2020). These methods can be further expanded to incorporate consumption-based per-capita targets and the methodology of modeling lifestyle changes proposed in this paper.

Second, future scenarios linked with lifestyle carbon footprints can be developed through stakeholder engagement processes such as with citizens, the business sector, community organizations, and policymakers. As the forms sustainable lifestyles will take depend on the contexts (Akenji and Chen 2016), so too will future decarbonized lifestyles. Stakeholder engagement can facilitate actions in policy and business sectors by comprehensively considering the implications for lifestyles of citizens and environmental, economic, and social consequences. The scenario making process can be used as a tool for communicating with non-scientific audiences and engaging stakeholders (Raskin et al. 2004). Studies developing future lifestyle scenarios with stakeholder engagement (Leppänen et al. 2012; Vita et al. 2019) can be extended to explicitly link consumption-based footprint targets to investigate the desired types of transitions. Making use of such participatory processes can ensure the views of citizens and stakeholders are reflected in the desired actions, to achieve a high quality of life within climate boundaries.

Finally, the extent and level of ambition of lifestyle changes required to meet the target necessitate supporting measures and stakeholder actions. Unsustainable patterns of consumption are deeply embedded in contexts linked with everyday routines and practices (Evans and Jackson 2007; Salomaa and Juhola 2020). Systems of provisioning linked with social practices have crucial roles beyond behaviors of citizens (Spaargaren and Oosterveer 2009). Therefore, instead of placing overall responsibility entirely in the hands of each consumer, a transition to decarbonized lifestyles may instead require systemic actions through all stakeholder actions. This calls for supporting measures through new systems of provisioning as well as policies to enable decarbonized lifestyles, which can be identified and supported through developing roadmaps alongside the scenarios.

Scenarios are often combined with roadmapping of necessary actions along with timelines, as illustrated in low-carbon society scenarios (Kainuma et al. 2012), sustainable lifestyle scenarios (Leppänen et al. 2012; Impiö et al. 2020), and technology roadmapping (Hussain et al. 2017). Stakeholder dialogues such as workshops can help incorporate different perspectives in roadmapping, as illustrated in existing studies (Doyle and Davies 2013). Roadmaps to support and enable decarbonized lifestyles can include various instruments and actions related to consumer lifestyles, including economic, regulatory, information, nudging, infrastructure, and product and service provision. These actions should cover and focus on the carbon footprint hotspots related to nutrition, housing, mobility, consumer goods, leisure, and services identified in this paper.

The research opportunities discussed above are mutually linked and may have synergies. The subnational analysis of lifestyle carbon footprints can provide a useful background that informs in the areas of equitability and effectiveness of actions in the scenarios. In addition, options identified as part of the scenarios through the participatory process can be tested in living labs to identify supporting measures and constraints in real-life environments, and the learnings from the living labs approach can be reflected into roadmaps.

Conclusions

The present paper proposes an approach that can be taken to assess lifestyle carbon footprints and to facilitate lifestyle changes towards the 1.5 °C climate goal, based on the key findings in the "1.5-Degree Lifestyles" phase I project. Some of the research opportunities articulated in this paper, including subnational analysis of lifestyle carbon footprints, integration with living labs, and participatory scenario development are currently being applied to the subsequent phase of the "1.5-Degree Lifestyles" project, which involves more countries.

To date, demand-side solutions including consumption, behaviors, and lifestyles have been insufficiently addressed in the research on climate change mitigation (Creutzig et al. 2018). Considering the magnitude of changes required, lifestyles need to be decarbonized based on a transformative approach with a focus on non-incremental changes embracing higher-order, larger-scaled, deep and impactful, systemic changes towards the long-term targets as proposed in this paper. The findings from this paper confirm that focusing on impactful lifestyle changes in terms of carbon footprint reduction potential is crucial, as pointed out by a previous review study (Wynes and Nicholas 2017). Despite the large mitigation impacts expected from lifestyle changes, consumer lifestyles are deeply embedded in complex cultural contexts, social practices and provisioning systems. To address the magnitude of required changes, a transformation of lifestyles may need to employ mutually enhancing dual approaches, through voluntary efforts and movements by citizens and facilitation through policies and stakeholder actions to support decarbonized options while discouraging unsustainable ones. This multi-stakeholder view can be facilitated through the research opportunities discussed in this paper.

Implementing the research opportunities discussed in this paper may require a highly interdisciplinary approach, including but not limited to engineering, sociology, behavior sciences, economics, and policy sciences. Such research efforts can contribute to a transdisciplinary approach to advance sustainability science and address its various complexities, which include human behavior, norms and culture, and socio-ecological systems (Shrivastava et al. 2020). The approach suggested in this paper can be used to advance both academic and practical knowledge on how to facilitate the transition of lifestyles necessary to meet the 1.5 °C climate goal.

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