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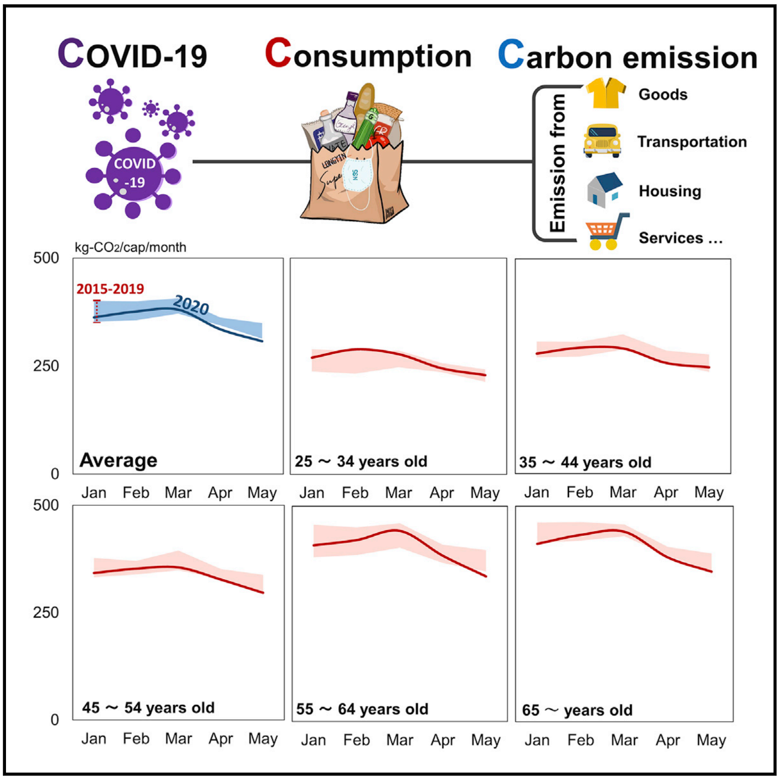
Negligible impacts of early COVID-19 confinement on household carbon footprints in Japan

Graphical abstract



Highlights

- Lifestyle and consumption changes for Japanese households during COVID-19 pandemic
- Negligible changes in household carbon footprints compared with 2015–2019 levels
- Carbon footprint trade-offs between certain consumption categories
- Age-differentiated carbon footprints show minor deviations from 2015–2019 trends

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In brief

The COVID-19 pandemic caused significant changes in the lifestyles and household consumption patterns of Japanese households. However, these changes had negligible effects on household carbon footprints both on aggregate and in age-differentiated terms. Despite some trade-offs between consumption categories, carbon footprints reversed rapidly to the levels observed in previous years.

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Negligible impacts of early COVID-19 confinement on household carbon footprints in Japan

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SCIENCE FOR SOCIETY Households are major sources of greenhouse gas (GHG) emissions both directly through energy use for transport, heating, and other activities and indirectly through emissions embedded in the goods and services they consume. Changes in lifestyles and consumption patterns can have major ramifications for GHG emissions. The COVID-19 pandemic catalyzed profound and rapid lifestyle shifts, which makes it a natural experiment for studying the outcomes of such changes for GHG emissions. Despite shifts in the work, socialization, and consumption practices of Japanese households during the early stages of the pandemic (January–May 2020), the overall changes in carbon footprints were negligible. Despite some trade-offs between consumption categories, the general carbon footprint patterns remained similar to 2015–2019 trends and are consistent among age groups. This has implications for decarbonization efforts in that the environmental benefits of changes in consumption patterns might not materialize automatically and be easily reversible.

SUMMARY

The rapid and extensive changes in household consumption patterns during the coronavirus disease 2019 (COVID-19) pandemic can serve as a natural experiment for exploring the environmental outcomes of changing human behavior. Here, we assess the carbon footprint of household consumption in Japan during the early stages of the COVID-19 pandemic (January–May 2020), which were characterized by moderate confinement measures. The associated lifestyle changes did not have a significant effect on the overall household carbon footprint compared with 2015–2019 levels. However, there were significant trade-offs between individual consumption categories such that the carbon footprint increased for some categories (e.g., eating at home) or declined (e.g., eating out, transportation, clothing, and entertainment) or remained relatively unchanged (e.g., housing) for others. Furthermore, carbon footprint patterns between age groups were largely consistent with 2015–2019 levels. However, changes in food-related carbon footprints were visible for all age groups since March and, in some cases, since February.

INTRODUCTION

Coronavirus disease 2019 (COVID-19) emerged in late 2019[1] and has since caused an unprecedented disruption of social and economic activity globally. Billions of people were forced to change, on short notice, their behavior and lifestyle, including how they live, work, and socialize. Responses to the COVID-19 outbreak have varied significantly between countries, reflecting the very different national approaches and policies seeking to prevent or mitigate the spread of the disease. Some of the most common measures have included telecommuting, the scaling down (or even halting) of economic activity (e.g., services and industry), and stay-at-home orders of variable severity between countries.[2] Although a wide array of different control measures has been applied, at the time of writing this paper, according to the World Health Organization (WHO), there have been nearly 83.3 million confirmed cases in 220 countries[3] and second and third waves of infections in many countries.

Since the early phases of the pandemic, studies have noted that these major changes in human activity have had important economic and social ramifications.[4,5] This in turn seems to have had significant implications for the environment through the disruption of aggregate demand and global trade.[6] For example, studies have estimated substantial short-term decreases in greenhouse gas (GHG) emissions[7,8] nationally and globally, as well as locally in some emission hotspots.[9–12] However, the observed changes in socioeconomic activity might have more pronounced and long-term environmental implications, for example, by derailing current progress to (or providing new opportunities for) energy transitions and decarbonization.[13–15] Furthermore, many of the actual environmental outcomes seem to vary substantially between countries depending on their different approaches to containment measures.[16,17] Most of the studies mentioned above have explored the environmental outcomes of the COVID-19 pandemic through directly measuring environmental variables or identifying macro-level patterns associated with changes in aggregate economic and social activity. It can thus be argued that such studies have mainly adopted a production perspective.

However, there has been very little evidence of the possible environmental outcomes of the COVID-19 pandemic from a micro-level or consumer perspective, for example, by quantitatively exploring shifts in consumption patterns due to changes in the lifestyles of individuals and/or households. In the past, many studies have used such a lens to explore the direct links between the lifestyles of individuals and households, their consumption choices, and the impact on the environment,[18,19] e.g., carbon footprints of current and future lifestyles in the UK,[20] USA,[21] China,[22,23] and Japan,[24] among others. Other studies have identified the very diverse factors mediating the environmental impacts of lifestyles and consumption practices, such as household type,[25] income and wealth (and related inequalities),[26–30] and demographic processes (e.g., aging).[31–33]

At the same time, it has been argued that transitioning to more sustainable lifestyles, such as those characterized by lower mobility and/or consumption, could have major environmental benefits by decreasing overall energy consumption, GHG emissions, and environmental degradation.[19,31,34–37] For example, studies have pointed to the environmental dividends that a voluntary "downsizing" of the lifestyle has without necessarily compromising the quality of life.[15,38] However, despite the wealth of micro-level studies exploring the environmental outcomes of observed (and not simulated) lifestyle changes, these studies tend to have a piecemeal approach by focusing on small populations and/or distinct practices (e.g., mobility and dietary transitions).[39] Conversely, most studies exploring the environmental outcomes of large-scale lifestyle changes have relied on either simulations or long-term historical data.[40]

Given the above, the aim of this paper is two-fold. First, it assesses the changes in the direct and indirect GHG emissions associated with household consumption (carbon footprint) due to the large-scale lifestyle shifts during the early stages of the COVID-19 pandemic. Second, by viewing these shifts through the lens of a natural experiment,[41] it critically discusses the implications of possible large-scale lifestyle changes for decarbonization. This reflects the emerging view of many environmental scientists that the COVID-19 pandemic is an unprecedented natural experiment (e.g., the Global Human Confinement Experiment)[41] that can provide profound insights about the environmental outcomes of large-scale changes in human activity given its extensive and rapid effects on socioeconomic activity and human behavior.[41]

This study focuses on Japan, which offers an ideal setting in terms of its significant contribution to anthropogenic climate change, its distinct demographic and socioeconomic characteristics, and its response to the outbreak using much milder control policies than those in other countries. On the one hand, Japan is the world's third largest economy and fifth largest GHG emitter and has a highly affluent and consumerist society. On the other hand, Japan had a relatively unique response to the early COVID-19 outbreak, which did not entail a full or strict lockdown; instead, it influenced the restriction of usual behavior through mild measures.[42] This makes Japan arguably a better proxy of a more "reduced activity" lifestyle than most other developed countries that endured more severe measures. Furthermore, Japan has been undergoing profound demographic changes in terms of aging such that the proportion of persons >65 years old increased from 10% in 1985 to 28.1% in 2018 (one of the highest such fractions in the world).[43] This makes Japan an ideal setting for exploring the age-differentiated environmental outcomes of lifestyle change considering the observed trends toward higher affluence, consumerism, and population aging in many parts of the developed and developing world.[19]

In summary, we assess the carbon footprint of lifestyle changes for the period of January–May 2020 across a set of constituents of household consumption for different age groups and compare them with 2015–2019 levels. We use environmentally extended input-output (EEIO) analysis and data from a nationally representative sample of around 7,500 households, collected monthly by the Statistics Bureau of the Ministry of Internal Affairs and Communications of Japan. The study period consists of three relatively distinct time intervals characterized by (1) a lack of any marked lifestyle change (January–February), (2) a moderate visible lifestyle change (March), and (3) more pronounced changes during an initially partial and subsequently national state of emergency (April 7 to May 25) (Figure S1).

RESULTS

Carbon footprint fluctuation and trade-offs

Figure 1 shows the total carbon footprint associated with the different components of household consumption in Japan for 2020 (red lines) compared with 2015–2019 levels (green and yellow areas) and the major constituent of each consumption component for 2020 (pie charts). Overall, the results suggest that the total carbon footprint did not change throughout the period of January–May 2020 compared with the 5 previous years (2015–2019). Indeed, the total monthly carbon footprint for 2020 (red line) remained within the window of the carbon footprint of household consumption in the period 2015–2019 (green area) (Figure 1T). However, it is possible that lifestyle change slightly decreased the carbon footprint for the months of April and May considering that it reached the upper bound of the 2015–2019 carbon footprints for these months.

When looking at the disaggregated carbon footprint for individual consumption categories, as expected, there are large overall declines for activities affected by the confinement measures, such as eating out (Figure 1I), entertainment (Figure 1S), and clothing (Figure 1O). On the contrary, as expected, the carbon footprint for most consumption categories associated with

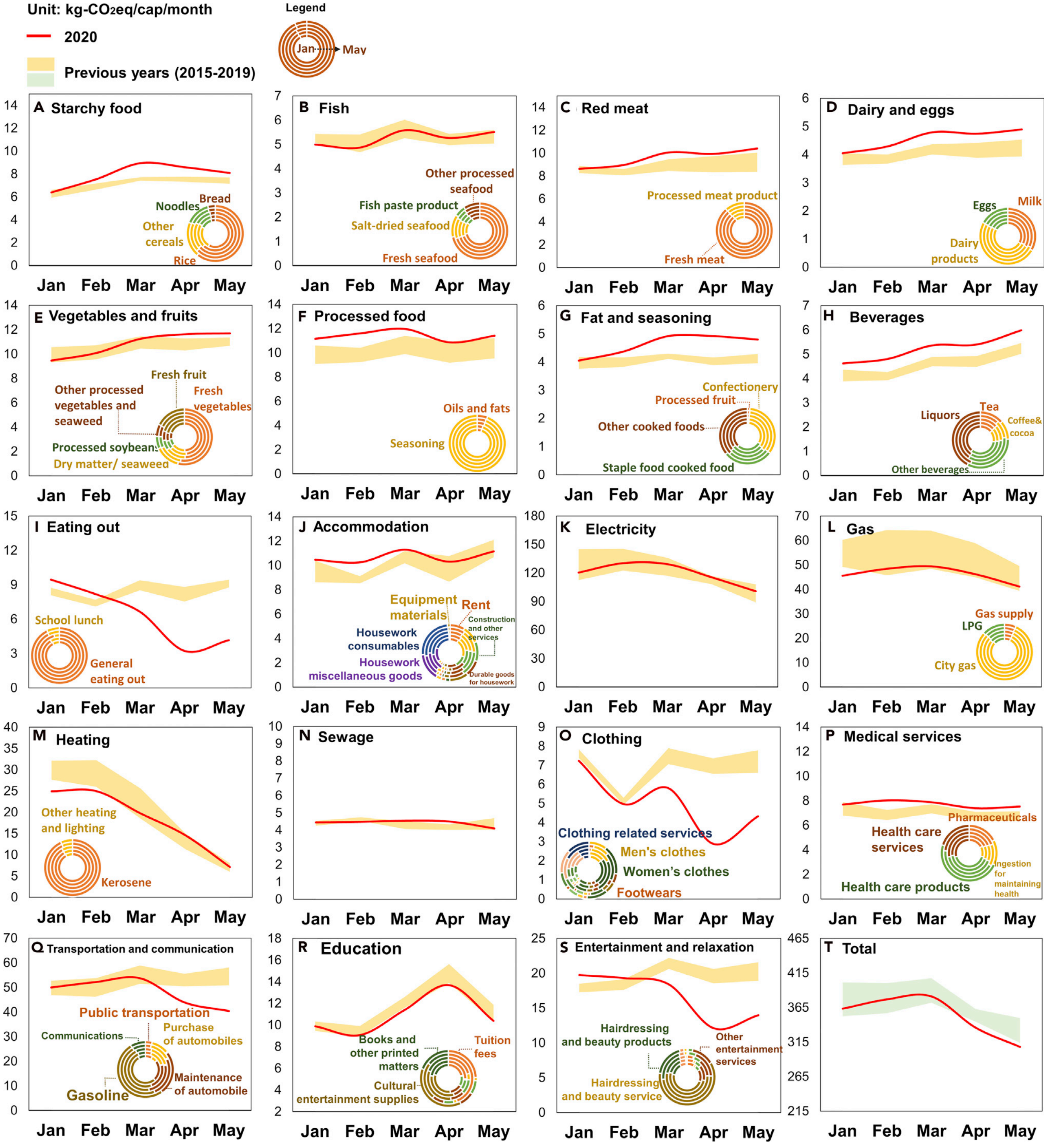

Figure 1. Total carbon footprint of household consumption (in kg-CO_2eq/cap)

The red line indicates the 2020 GHG emissions for the different household consumption categories for each corresponding month. The yellow and green areas indicate the emissions ranges for the past 5 years (2015–2019). Pie charts indicate the main emission sources for each consumption category.

eating at home increased substantially (Figures 1A–1H). For all these consumption categories, the footprint changes from 2015–2019 levels were very pronounced for March and April, which signify the months of major lifestyle change. However, the footprints for these consumption categories increased rapidly in May, which signifies the end of the confinement measures, although they did not reach the levels of the previous year.

The total transport-related emissions (both direct and indirect) followed similar trajectories as the 5 years before the outbreak (albeit a bit elevated in January and February) but fell well below the levels of previous years during April and May, when the confinement measures affected travel patterns for large segments of the population (Figure 1Q). This decline was mainly due to decreases in gasoline consumption for private vehicles, which fell 18% below the lowest emission levels of the 5 previous years. This seems to imply that even without mandatory control measures, Japanese residents substantially decreased their private vehicle use, even during the Golden Week in May, which is the major holiday period in Japan.

Surprisingly, despite this reduced-activity lifestyle, the carbon footprint of housing-related consumption categories, such as accommodation, electricity, gas, heating, and sewerage, remained largely within the range window of the past 5 years with some small exceptions (Figures 1K–1N). Although the carbon footprint of most these consumption categories hovered at the higher end of the past footprint spectrum (except for gas), especially during the confinement measures, they did not show any significant variation despite the larger amount of time that residents spent at home. The reason might have been that the decreasing demand for space heating due to the regular seasonal warming from March might have caused a "weekend" effect on the COVID-19 impact on housing-related emission rather than any unusually high temperatures compared with those in previous years (Figure S2). The carbon footprint of other household consumption categories, such as medical services and education, was close to past footprint levels such that the former stayed at the higher end of the spectrum and the latter stayed at the lower end of the spectrum (Figures 1P and 1R).

These patterns suggest two major things. First, despite the major lifestyle changes, the aggregate carbon footprint of household consumption seems to have remained relatively constant in comparison with previous years, although there are some signs of a slight increase. However, there were very pronounced changes in the carbon footprints of some consumption sub-components, which started bouncing back to the levels of previous years very rapidly after the lift of the state of confinement measures, such as eating out, clothing, and entertainment.

Age-differentiated carbon footprints

Figures 2 and 4 show the carbon footprint of non-food and food household consumption categories, respectively, differentiated by age group. Figure 3 provides a more disaggregated view of the age-differentiated emissions related to the demand on energy, sewage, and transportation.

Consistent with aggregate carbon footprint trends (Figure 1), the carbon footprint for most non-food household consumption categories remained almost within previous years' footprint limits for all age groups. However, there have been some major differences between consumption categories as explained below.

First, similar to the aggregate carbon footprint (Figure 1), the largest carbon footprint decreases observed during the pandemic across all age groups are clothing (Figure 2F), transportation (Figure 2H), and communication, entertainment, and relaxation (Figure 2J). For these consumption categories, their 2020 emission levels started falling below the 2015–2019 levels from March 2020 onward (since the early parts of outbreak in Japan) and further decreased very significantly in the subsequent months across all age groups.

Second, the age-differentiated carbon footprints for housing and related energy use (Figures 2A–2D) seemed to have remained within the previous years' footprint limits during the pandemic period despite major changes in working conditions (i.e., promotion of remote working) and socialization activities (i.e., request by Japanese government to avoid crowding). Regardless of the month and age group, the main elements of housing-related emissions were from electricity and natural gas (Figure 3), which might explain the increase by age in Figure 2D. When we look in more detail at energy-use patterns (Figures 2B–2D and 3), we see that as temperature increased into the spring season, heating demand decreased appreciably. Interestingly, emissions linked to sewage showed a slight increase in April 2020 among age groups >45 years old in comparison with previous years, but it is not clear why this happened. Although it could have been due to increased hand washing for sanitary purposes, the lower-than-average sewage emission in May for all groups might challenge this hypothesis.

Third, there was a pronounced decline in transportation-related emissions in May, when the confinement measures affected travel patterns for large segments of the population, especially groups between 40 and 64 years old. Interestingly the transportation emissions of younger groups in May were similar to those in previous years but much lower for elderly groups, possibly implying the normalization of travel activities for the former during Golden Week (which is the main holiday period in Japan) and the continuation of a more reduced-activity lifestyle for the latter.

When we look more closely at the different food-consumption categories, some interesting patterns emerge (Figure 4). First, although the confinement measures were implemented in April and May, changes in food-related carbon footprints were visible for all age groups since March and, in some cases, since February (see below) considering that Japan was one of the first countries to record COVID-19 infections. Although it is possible that some of the increased consumption (and related carbon footprint for some food categories) came from panic buying in February and March, as possibly implied by the increased footprint of starchy and processed food that reached the emission levels of previous years (Figures 4A and 4F), there were also very visible increases during April and May 2020 from more perishable items, such as red meat, eggs and dairy, and fresh vegetables and fruit (Figures 4C–4E). There was a marked and consistent increase in the carbon footprint of eating at home across all age groups such that the April 2020 levels were consistently higher than the highest related footprint of the past 5 years. In contrast, the patterns for the carbon footprint of eating out were exactly the opposite (Figure 4B). However, we note that we cannot infer from these results whether dietary change took place during the confinement measures or its effect on GHG emissions. This is because all of the distinct food categories in Figure 4 relate to eating in, and in the Family Income and Expenditure Survey (FIES), expenses for "eating in" are divided across food categories. However, "eating out" in the FIES is captured as a single expense category not

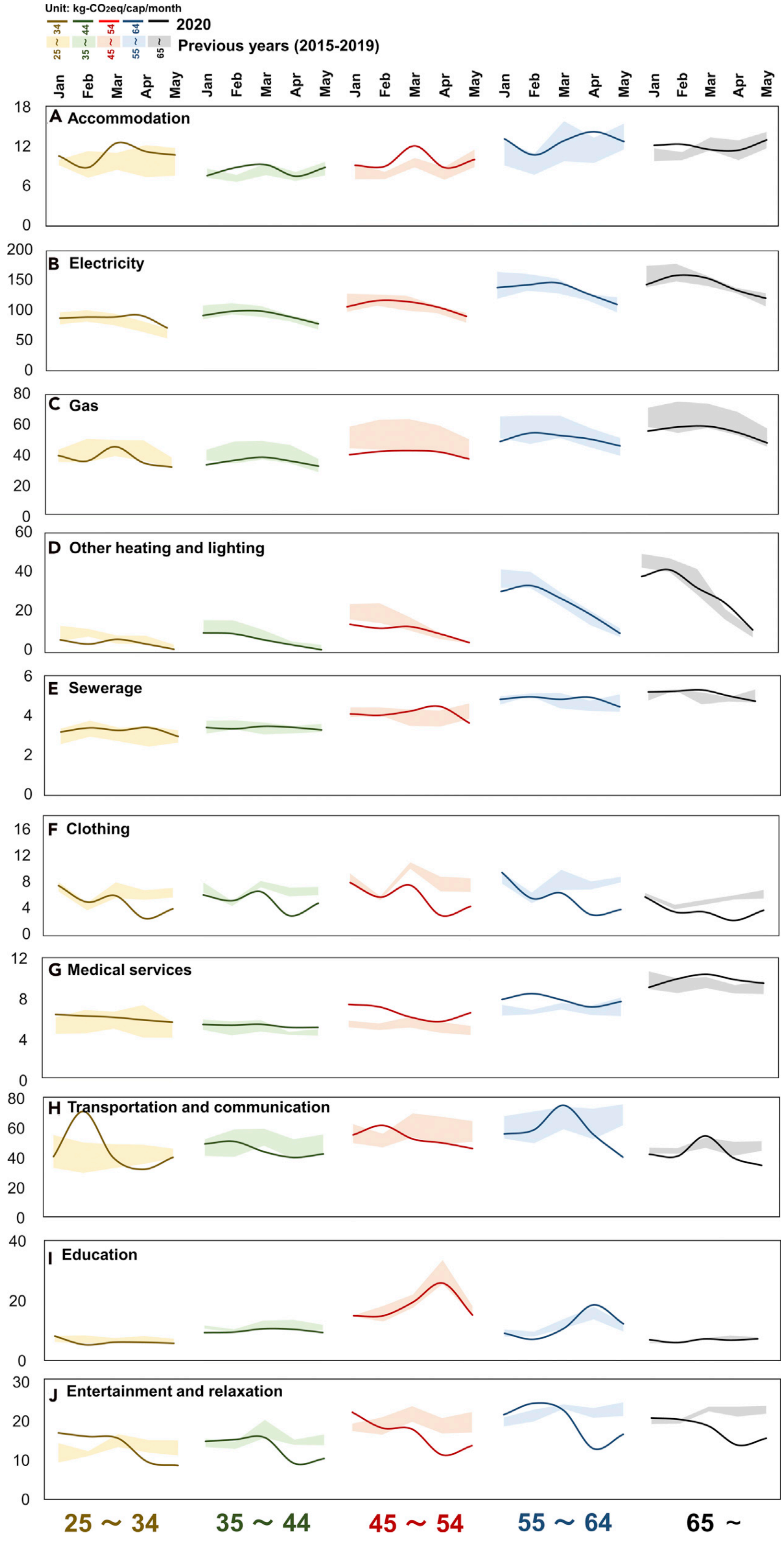

Figure 2. Carbon footprint of non-food consumption categories disaggregated by age group (in kg-CO$_2$eq/cap)

The lines indicate the 2020 GHG emissions for the different non-food household consumption categories for each corresponding month. The shades indicate the emissions ranges for the past 5 years (2015–2019).

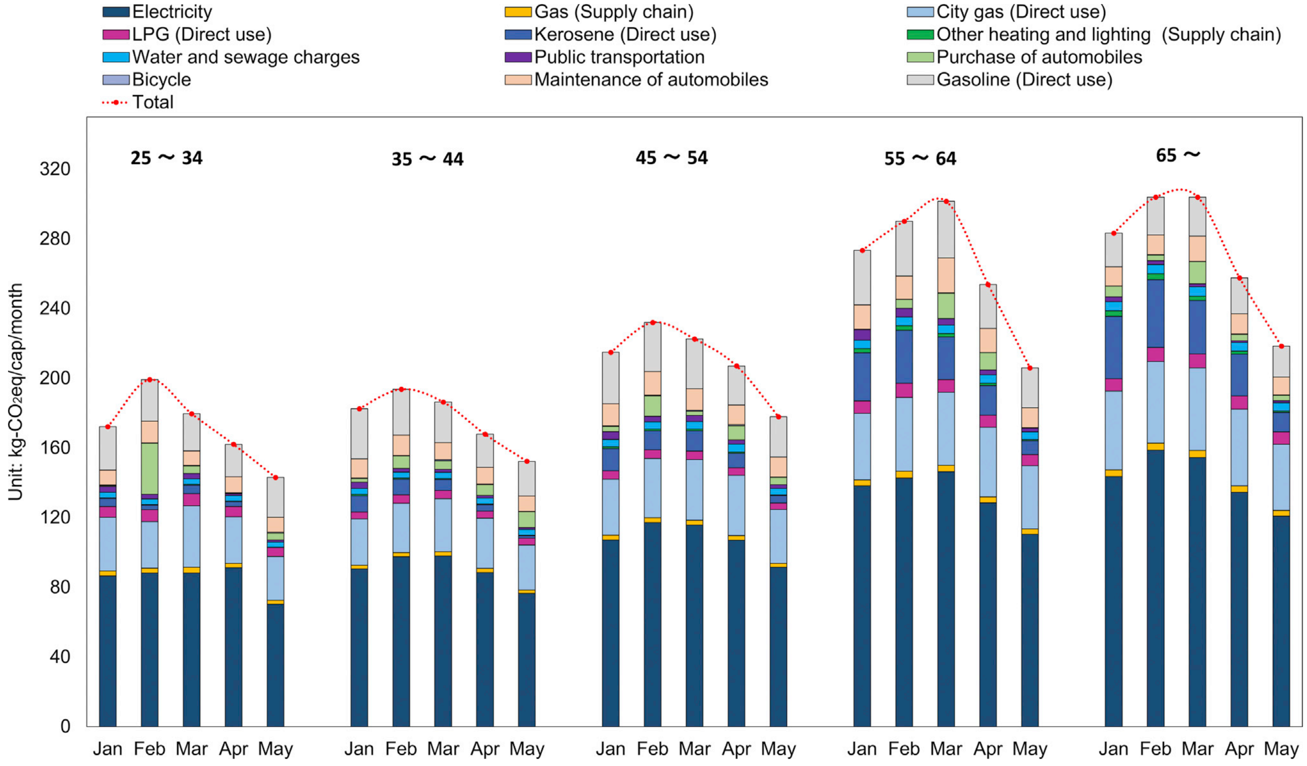

Figure 3. Carbon footprint components for housing, sewage, and transportation by age group (in kg-CO_2eq/cap)

differentiated by food item. In other words, the results of Figure 4 should not be used to elicit whether dietary change occurred or the associated changes in emissions.

Finally, when looking more closely at the footprint of the different age groups, we see some interesting patterns. The most important is that despite some differentiation in the footprints of individual age groups for some specific consumption categories, there is no major change in group ranking or order for the aggregate footprint and almost all individual consumption categories, except for transportation demand. This suggests that no age group disproportionally altered its behavior during the period of confinement measures in comparison with behavior in previous years and that although the younger household cannot wait to go out in May, the elderly generation still leads a reduced-activity lifestyle.

DISCUSSION

Negligible carbon footprint impacts of lifestyle change

The results strongly imply that lifestyle change during the COVID-19 outbreak period did not have an appreciable effect on the carbon footprint of household consumption in Japan, apart from a small decline below past levels for May (Figure 1). This finding, based on micro-level data, comes in contrast to macro-level studies suggesting that in the same period the decline in economic activity and trade around the world during the COVID-19 outbreak precipitated large overall declines in production-side GHG emissions.[6,9,44–47]

This suggests a rather different trajectory of GHG emissions patterns from the household sector compared with other economic sectors, at least during the early months of the COVID-19 pandemic (February–May 2020). However, we cannot preclude the possibility of more substantial emission reductions in the medium to long term as a result of reduced household consumption influenced by a possible economic downturn in the aftermath of the COVID-19 outbreak.[48]

Lifestyle change has had relatively consistent effects on age-differentiated carbon footprints. Even though the absolute carbon footprint levels are higher, on average, for more elderly groups, there does not seem to be any major shift in the ranking of carbon footprints between age groups (Figures 2 and 4). It is worth noting that elderly groups have the highest per capita carbon footprints, especially for energy-related categories, regardless of the month or year (e.g., pandemic versus regular year). These generally higher emissions of elderly households have been emphasized in other studies in Japan[31,33,49] and are mainly due to due to higher heat needs and cooking.[50] In our case, the transport-related emissions of elderly households remained low even after the emergency declaration in May, and the total footprint was not significantly affected because neither emissions from electricity nor food consumption showed a substantial decline in comparison with previous years.

Trade-offs among consumption categories

Lifestyle change does not seem to have precipitated uniform and proportional changes in carbon footprints across consumption categories. Instead, there seemed to be substantial variation in carbon footprint patterns among consumption categories such that the main observed carbon footprint trade-offs was observed between consumption categories associated with eating at

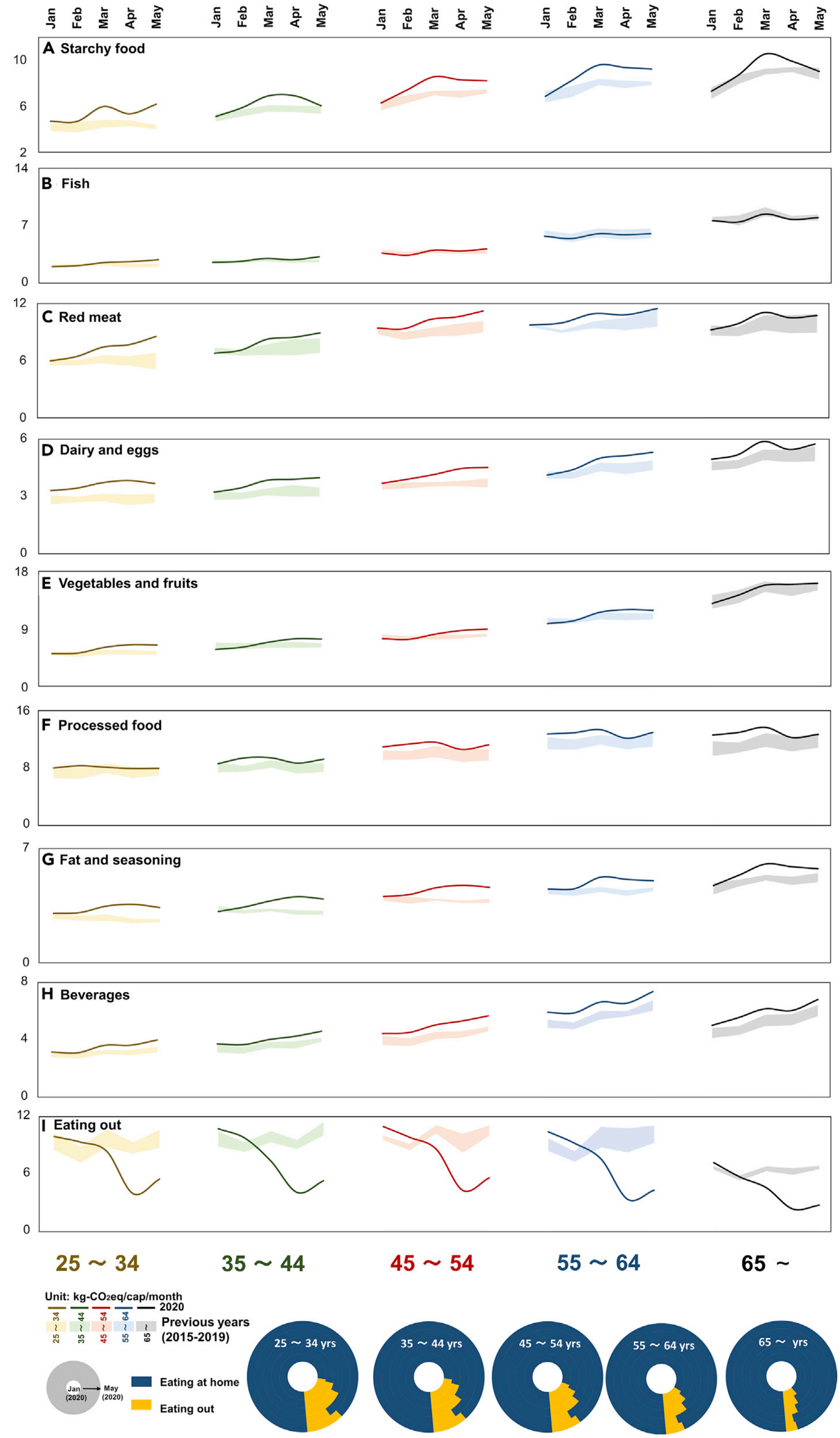

Figure 4. Carbon footprint of food consumption categories disaggregated by age groups (in kg-CO_2eq/cap)

The lines indicate the 2020 GHG emissions for the different food-related household consumption categories for each corresponding month. The shades indicate the emission ranges for the past 5 years (2015–2019). The concentric circles at the pie charts indicate for each age group the proportion of eating at home (dark blue) and eating out (light blue) to the food-related carbon footprint by month from January (inner circles) to May (outer circles).

home (major increase) and eating outside, transport, clothing, and entertainment (major declines). Surprisingly, and with few exceptions, the reduced-activity lifestyle does not seem to have substantially affected the carbon footprint of housing even though the opposite trends were visible in some other developed countries.[51]

Even though people spent more time at home, the lack of any major changes in the carbon footprint of housing (and other related consumption categories) might be explained by the timing (spring) and seasonality of energy consumption in Japan.[33] Heating and cooling are the largest contributors of housing-related emissions in Japan,[33] but the mild weather during late spring in Japan reduces the need for both heating and cooling, as is quite evident in past footprint patterns for these categories (Figures 1K–1M). It is worth mentioning that the 2020 spring period did not experience any abnormal warming in that the average temperatures were rather similar to those in past years (Figure S2). However, we cannot preclude that a reduced-activity lifestyle could increase the housing-related carbon footprint during the winter or summer as a result of the higher demand for heating or cooling, respectively.

The most pronounced carbon footprint shifts are linked to changes in eating habits, especially the large increase in eating at home. This seems to have negated any carbon footprint gains from other consumption categories due to lifestyle change given that these changes were largely consistent between all age groups (Figure 4). Despite some evidence of precautionary food purchasing during the early part of the outbreak (i.e., indicated by carbon footprint increases for processed and starchy food in February and March), the subsequent increase in consumption and carbon footprints of perishable food items shows a rather clear-cut change in eating habits during the study period. This is quite visible in the large increase in the carbon footprint of emission-intensive food categories, such as red meat, dairy, and eggs,[40] especially after March. Even though it is not possible to confirm possible dietary change from this highly aggregated data, such shifts might have happened and can have major environmental ramifications considering that Japan imports most of these food items from other countries.[52]

Implications for decarbonization

Before exploring the implications of this study for decarbonization efforts through the lens of a natural experiment, we should first acknowledge two important points. First, as outlined in the introduction, Japan offers a rather interesting case for exploring the ramifications of reduced social and economic activity given that the confinement measures were rather moderate and largely voluntary.[42] Thus, compared with those in other countries, they could in theory better reflect a possible switch to a reduced-activity lifestyle. However, at the same time, Japan has some specific characteristics that might affect generalization to a degree. These include its mild spring, relatively small homes, and low reliance on car use, especially in large metropolitan areas, such as Tokyo, where a large proportion of the population resides.

That said, our results suggest that, contrary to other economic sectors and geographical contexts,[6,9,44–47] there seemed to be no obvious short-term environmental benefits from the lifestyle change in the Japanese household sector during the COVID-19 confinement measures. In our mind, this has a major ramification for contributing to decarbonization through lifestyle change in that environmental benefits might not materialize simply from adopting a reduced-activity lifestyle. In fact, the evidence suggests that there was a simultaneous shift in consumption patterns, which seems to have practically negated any environmental benefits, at least in the short term. Furthermore, the quick bounce of carbon footprints to pre-confinement levels strongly implies that any changes might be easily reversible.

This seemingly minor environmental effect of this involuntary change in consumption patterns across all age groups seems to be in stark contrast with the pronounced positive environmental outcomes of voluntary lifestyle changes.[15,38] In this sense, we see two major ramifications of our results for influencing decarbonization through lifestyle change. First, in our mind, it re-affirms the real importance of education to foster more sustainable lifestyles and prolonged shifts in consumption patterns[19,40,53] if lifestyle change is to contribute meaningfully to decarbonization efforts. Second, considering the larger per capita footprints of the ever-increasing elderly population, future decarbonization efforts through lifestyle change should focus on emission-intensive household demand, such as space and water heating and private car use.

Future perspectives

Future studies should seek to bridge some of the limitations of this study. Methodologically, these include the inability to consider properly the carbon intensities of imported goods and the consumption of single-person households (see the limitations section in the experimental procedures). The former would require the development of multi-regional input-output (MRIO) tables that have high sectoral resolution and use recent datasets that can capture national economic structure well to go beyond simple calculations based on GDP change. This is, to our best knowledge, a major research gap for Japan in that most current studies are unable to use such high-resolution MRIOs.[24,54] The latter would possibly require dedicated primary data-collection campaigns from nationally representative singe-person households because these are not considered in the underlying consumption datasets collected by the Japanese government and used in this study (see experimental procedures).

More broad studies should seek to explore the effects of different confinement measures on GHG emission changes due to lifestyle changes. Arguably, as outlined in the introduction, Japan's confinement measures have been rather mild in comparison with those of other developed countries, which in our mind makes them a better approximation of reduced-activity lifestyles. However, comparative studies across different countries could provide better micro-level evidence of how the "Anthroposause" has affected the environment, which would better complement the emerging studies from the macro-level.[55–57]

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Yin Long (longyinutokyo@gmail.com).

Materials availability

This study did not generate new unique materials.

Data and code availability

The dataset used for this paper has been uploaded to the figshare data repository, where it is freely available at https://doi.org/10.6084/m9.figshare.14211989.v1.

Carbon footprint of household consumption

Household consumption emits GHGs both directly and indirectly. The direct emissions are due to the actual consumption of fuel, such as natural gas and petroleum products by households. Indirect emissions refer to the emissions embodied in the different goods and services consumed by households, such as food and consumer products. Thus, the total carbon footprint of household consumption (E^i) is estimated as the sum of direct (E^i_d) and indirect (E^i_{cf}) emissions (Equation 1).

$$E^i = E^i_d + E^i_{cf}. \qquad \text{(Equation 1)}$$

In this study, we estimate the total carbon footprint of household consumption for the period of January–May 2020 and compare it with 2015–2019 levels to identify the effect of lifestyle changes during the first COVID-19 confinement measures in Japan. The GHGs considered in the calculations include CO_2, CH_4, N_2O, HFC_S, PFC_S, SF_6, and NF_3.

Indirect emissions

Many studies have argued for the importance of tracking indirect emissions when evaluating the environmental consequences of household consumption.[58–62] Indirect emissions can be estimated through EEIO analysis,[6,31,54,63,64] which involves the use of an economic input-output table (IOT). IOTs were originally used to estimate economic transactions among industrial sectors.[65–67] However, subsequently they have found applications in environmental impact assessment as a means of tracking indirect energy flows and emission transfer.

In the EEIO model, the relationship between final consumer demand and its environmental impacts can be expressed through Equation 2:

$$\boldsymbol{X} = (\mathbf{I} - \boldsymbol{A})^{-1} F\,, \qquad \text{(Equation 2)}$$

where $\boldsymbol{X}$ is the vector of domestic production, $\mathbf{I}$ is the identity matrix, $\boldsymbol{A}$ is the input coefficient matrix, and $\boldsymbol{F}$ is the vector of final demand. When the effects of imported goods are considered, then the emission intensity of economic sectors is instead calculated with the $(\mathbf{I} - \boldsymbol{A}^d)^{-1}$ type, which refers to inverse matrix coefficients of "non-competitive import type," used for analysis when the input ratios of imports vary between sectors.[68] When considering the effect of imports, Equation 2 is modified into Equation 3:

$$\boldsymbol{X} = \left(\mathbf{I} - \boldsymbol{A}^d\right)^{-1} \boldsymbol{F}^d\,, \qquad \text{(Equation 3)}$$

where $\boldsymbol{A}^{\mathbf{d}}$ and $\boldsymbol{F}^{\mathbf{d}}$ represent the vectors of domestic input coefficients and domestic final demand, respectively. Then, combined with the household consumption inventory, indirect emissions embodied in consumption are quantified according to Equation 4:

$$E^i_{cf} = \sum_{j=1} e^i_j * \left(\mathbf{I} - \boldsymbol{A}^{\mathbf{d}}\right)^{-1} * Ep^i\,, \qquad \text{(Equation 4)}$$

where E^i_{cf} indicates the household carbon footprint by consumption item i, Ep^i refers to monetary consumption on consumption item i, and e^i_j is the direct emission intensity of consumption item i's GHG emission j. By multiplying the Leontief inverse matrix, the direct emission intensity is converted into indirect emission intensity, i.e., $\sum_{j=1} e^i_j * (\mathbf{I} - \boldsymbol{A}^{\mathbf{d}})^{-1}$, denoting the indirect emission intensity of item i.

Direct emissions

Direct emissions are due to the use of fossil fuel, such as natural gas and other petroleum products. For this study, we include the emissions associated with the use of city gas (pipe gas), liquefied petroleum gas (LPG), kerosene, and gasoline. Japanese households do not use coal directly, whereas kerosene is an important fuel for space heating, especially in the mountainous regions.[50] The direct emission is estimated through Equation 5,

$$E^{dr}_{y,m} = \sum_{i=1} e^i_t * Ep^i_{y,m} * Upc^i_{y,m} \qquad \text{(Equation 5)}$$

where $E^{dr}_{y,m}$ indicates the total direct household emissions in year y month m, Ep^i is the direct monetary on fuel i, $Upc^i_{y,m}$ is the unit price of fuel i in year y and month m, and e^i_t is the emission intensity of fuel i in year y derived from the Agency for Natural Resources and Energy by year.[69,70]

To analyze total direct emission by household activities, we merged the four direct emission types with the indirect emission inventory and reclassified sectors according to household demand. In more detail, gasoline-related emissions are merged with other transportation-related indirect emissions into the "transportation and communication" sector, city gas and LPG in gas-related emissions are merged with indirect upstream emissions into "gas," and kerosene is placed into the "heating" sector.

Datasets and IOTs

The base data for household consumption used for calculating the indirect and direct emissions come from the monthly FIES,[71] conducted monthly across Japan by the Statistics Bureau of the Ministry of Internal Affairs and Communications. The FIES follows a standardized approach to capture the expenditures of a nationally representative sample of 7,500 households per month across the country.

The data for the indirect emission intensity of household consumption come from the Embodied Energy and Emission Intensity Data for Japan Using Input-Output Tables (3EID), a database of Japan's sectoral intensity of lifecycle environmental burdens. This is constructed from the IOTs for Japan with the EEIO model developed by Nansai et al.[72,73] Even though the original model was developed in 2002, it is updated regularly on the basis of Japan's official IOT. For our calculations, we used the GHG emission intensity for each final demand sector included in the last updated version of the 3EID, developed for the year 2015.

We select the 3EID, which is a single-regional input-output (SRIO) table, rather than a MRIO table for two reasons: (1) higher sectoral resolution and (2) most recent data availability. In more detail, the 3EID has a much higher sectoral resolution (390 sectors) than other MRIOs, such as WIOD (56 sectors) and EXIOBASE (200 sectors), which is closer to the structure of the FIES, which contains 500 consumption categories. This allows for a more comprehensive and fine-grain analysis of consumption changes in the Japanese household sector, which provides a much better correspondence between category model and data (see below). Furthermore, the 3EID model has more recent data availability than other SRIOs with similar sectoral resolution, such as Eora (401 commodities). In particular, although both 3EID and Eora produce recent data, the latter produces data that are an extension of estimates based on GDP and other information. Thus, it does not reflect the latest IOT structure information for Japan, which is necessary considering the span of our study (2015–2020).

Calculation procedure

First, we extract from the 3EID dataset the data for the 390 sectors for the year 2015, as well as the corresponding emission intensities.[72,73] Second, we match categories of the 3EID and FIES given that the classification of industries in the 3EID database differs from the classification of consumption elements in the FIES expenditure data. We matched the data according to the general approach outlined in Jiang et al.,[24] as shown in Table S1, which includes the major categories and cross-matching of FIES and 3EID. It should be noted that there is no perfect match between the categories of 3EID and FIES. Some 3EID categories, such as waste management, that are not distinct household components in FIES are linked to consumption-relevant items, such as municipal services. However, to avoid mismatching, we excluded some of the FIES miscellaneous expenses, such as allowances and donations, that cannot match well with 3EID sectors. According to our estimates, the average consumption ratio of these miscellaneous expenses was 4.65% for the study months in 2020, which represents a rather minor fraction of overall household consumption.

Third, we calculate changes in prices between years while adjusting for inflation and consumer price index (CPI). Here, we applied the constant price of

2015 according to the annual inflation data derived from the Word Bank.[74] Monthly average CPI was obtained from the Statistics Bureau of Japan.[75]

Fourth, we aggregate the obtained inventory of the 495 indirect emission items and 4 direct emission items into 19 footprint elements by month and age group (see Table S2 for 2020 levels). To understand convergences and divergences with past emission patterns, we compare each footprint element per month and age group for 2020, with the maximum and minimum such values between 2015 and 2019 (footprint range window).

Finally, it is worth mentioning that some of the interannual variation in emissions might be due to confounding factors related to climate and the economy. To test whether such confounding factors might have had an important effect on the results, we check for the study period in 2020 changes for three confounding factors related to the national economy and climate, namely GDP, household income, Engel's coefficient (i.e., proportion of income spend on food), and temperature. Overall, we find that these factors remain relatively constant between years such that there are no unnatural peaks or declines in the study period compared with previous years (Figures S3–S5).

Methodological limitations

Despite the high resolution of consumption categories and data quality, this study has three main limitations, namely (1) the inability to apply distinct carbon intensities for imported goods, (2) an inability to capture single-person households, and (3) the assumption of constant technology since 2015 and value-chain configurations since the onset of the COVID-19 pandemic.

First, the 3EID is an emission inventory generated through the Japanese SRIO table. This inherently means that the emission intensities used in this study reflect only domestic goods (and their value chains). We also apply these domestic emission intensities for imported goods, which inserts some level of uncertainty into our results. As outlined above, despite the higher sectoral resolution and data quality expected from adopting the 3EID model, this omission might underestimate the actual carbon footprint given that goods imported in the domestic market tend to have longer value chains and thus higher GHG emissions than similar domestic goods.[76] However, apart from the Global Link Input-Output for 2005,[73] to the best of our knowledge no IOT in the Japanese context has included multi-regional economic interactions or other similar data in an appropriate manner. This inability to consider properly emissions from imported good has remained a broader gap in the literature in recent decades.

Second, the underlying FIES datasets used in this study do not capture single-person households given that the most recent sample used in this study contains only households with two and more members. Even though single-person households are very prevalent across all age groups in Japan,[71] they tend to be more prevalent across younger age groups,[77] which are generally associated with lower per capita emissions in the country (also see the results section). At the same time, single-person households are associated with higher per capita emissions in Japan.[77] This means that it is difficult to predict what the actual effect of this omission is from our calculations in terms of overestimation, underestimation, or balancing out. Thus, considering the relatively large prevalence of single-person households in Japanese society,[78] some caution should be exerted when generalizing the results of the analysis.

Third, considering that 3EID data are for 2015, it might be that technology effects will lead to the over- or underestimation of the carbon footprints when applied for other years.[73,79] Still, we believe that these changes might be relatively marginal considering that improvement in technology needs a comparatively longer time to manifest.[80] One interesting phenomenon might be the effect of COVID-19 on production and trade chains given the severe economic disruptions. It is rather difficult to predict the effects of such changes for household carbon footprints in Japan. Considering the exclusion of imported carbon intensities in our analysis, as explained above, they will not affect the results of this analysis. In any case, we expect them to be marginal because it is highly possible that most materials were supplied to the market before the confinement measures, and thus non-food items (and possibly food items with long shelf lives, such as starchy and processed food) will not have been affected by any changes in production value chains due to existing stocks.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2021.03.003.

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AUTHOR CONTRIBUTIONS

Y.L. and G.A. designed the study. Y.L. conducted the analysis. Y.L and A.G. wrote the first draft of the manuscript. K.K., D.G., and G.A. revised the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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REFERENCES

1. World Health Organization (2020). Report of the WHO-China Joint Mission on Coronavirus Disease 2019 (COVID-19). https://www.who.int/docs/default-source/coronaviruse/who-china-joint-mission-on-covid-19-final-report.pdf.
2. Habersaat, K.B., Betsch, C., Danchin, M., Sunstein, C.R., Böhm, R., Falk, A., Brewer, N.T., Omer, S.B., Scherzer, M., Sah, S., et al. (2020). Ten considerations for effectively managing the COVID-19 transition. Nat. Hum. Behav *4*, 677–687.
3. World Health Organization (2020). Coronavirus disease (COVID-19) pandemic. https://www.who.int/emergencies/diseases/novel-coronavirus-2019.
4. Bonaccorsi, G., Pierri, F., Cinelli, M., Flori, A., Galeazzi, A., Porcelli, F., Schmidt, A.L., Valensise, C.M., Scala, A., and Quattrociocchi, W.J.P. (2020). Economic and social consequences of human mobility restrictions under COVID-19. Proc. Natl. Acad. Sci. USA *117*, 15530–15535.
5. Bartik, A.W., Bertrand, M., Cullen, Z., Glaeser, E.L., Luca, M., and Stanton, C.J. (2020). The impact of COVID-19 on small business outcomes and expectations. Proc. Natl. Acad. Sci. USA *117*, 17656–17666.
6. Long, Y., and Yoshida, Y. (2018). Quantifying city-scale emission responsibility based on input-output analysis—insight from Tokyo, Japan. Appl. Energy *218*, 349–360.
7. Guan, D., Wang, D., Hallegatte, S., Davis, S.J., Huo, J., Li, S., Bai, Y., Lei, T., Xue, Q., and Coffman, D.M. (2020). Global supply-chain effects of COVID-19 control measures. Nat. Hum. Behav. *4*, 577–587.
8. Le Quéré, C., Jackson, R.B., Jones, M.W., Smith, A.J.P., Abernethy, S., Andrew, R.M., De-Gol, A.J., Willis, D.R., Shan, Y., Canadell, J.G., et al. (2020). Temporary reduction in daily global CO_2 emissions during the COVID-19 forced confinement. Nat. Clim. Change *10*, 647–653.
9. Kanniah, K.D., Kamarul Zaman, N.A.F., Kaskaoutis, D.G., and Latif, M.T. (2020). COVID-19's impact on the atmospheric environment in the Southeast Asia region. Sci. Total Environ. *736*, 139658.
10. Long, Y., Huang, D., Lei, T., Zhang, H., Wang, D., and Yoshida, Y.J. (2020). Spatiotemporal variation and determinants of carbon emissions generated by household private car. Trans. Res. D. Trans. Environ. *87*, 102490.
11. Liu, Y., Huang, L., and Onstein, E. (2020). How do age structure and urban form influence household CO_2 emissions in road transport? Evidence from municipalities in Norway in 2009, 2011 and 2013. J. Clean. Prod. 121771.
12. Berman, J.D., and Ebisu, K. (2020). Changes in U.S. air pollution during the COVID-19 pandemic. Sci. Total Environ. *739*, 139864.
13. Kuzemko, C., Bradshaw, M., Bridge, G., Goldthau, A., Jewell, J., Overland, I., Scholten, D., Van de Graaf, T., and Westphal, K. (2020). COVID-19 and

the politics of sustainable energy transitions. Energy Res. Soc. Sci. *68*, 101685.

14. Steffen, B., Egli, F., Pahle, M., and Schmidt, T.S. (2020). Navigating the clean energy transition in the COVID-19 crisis. Joule *4*, 1137–1141.
15. Jackson, T. (2005). Live better by consuming less? Is there a "double dividend" in sustainable consumption? J. Indust. Ecol. *9*, 19–36.
16. Bahmanyar, A., Estebsari, A., and Ernst, D. (2020). The impact of different COVID-19 containment measures on electricity consumption in Europe. Energy Res. Soc. Sci. *68*, 101683.
17. Rugani, B., and Caro, D. (2020). Impact of COVID-19 outbreak measures of lockdown on the Italian Carbon Footprint. Sci. Total Environ. *737*, 139806.
18. Tukker, A., Cohen, M.J., Hubacek, K., and Mont, O. (2010). The impacts of household consumption and options for change. J. Indust. Ecol. *14*, 13–30.
19. Wiedmann, T., Lenzen, M., Keyßer, L.T., and Steinberger, J.K. (2020). Scientists' warning on affluence. Nat. Commun. *11*, 1–10.
20. Baiocchi, G., Minx, J.C., and Hubacek, K. (2010). The impact of social factors and consumer behavior on CO_2 emissions in the UK: a panel regression based on input-output and geo-demographic consumer segmentation data. J. Indust. Ecol. *14*, 50–72.
21. Bin, S., and Dowlatabadi, H. (2005). Consumer lifestyle approach to US energy use and the related CO_2 emissions. Energy Policy *33*, 197–208.
22. Ding, Q., Cai, W., Wang, C., and Sanwal, M. (2017). The relationships between household consumption activities and energy consumption in China—an input-output analysis from the lifestyle perspective. Appl. Energy *207*, 520–532.
23. Hubacek, K., Guan, D., Barrett, J., and Wiedmann, T. (2009). Environmental implications of urbanization and lifestyle change in China: ecological and water footprints. J. Clean. Prod. *17*, 1241–1248.
24. Jiang, Y., Long, Y., Liu, Q., Dowaki, K., and Ihara, T. (2020). Carbon emission quantification and decarbonization policy exploration for the household sector—evidence from 51 Japanese cities. Energy Policy *140*, 111438.
25. Shigetomi, Y., Nansai, K., Kagawa, S., and Tohno, S. (2018). Fertility-rate recovery and double-income policies require solving the carbon gap under the Paris Agreement. Resour. Conserv. Recycl. *133*, 385–394.
26. López, L., Arce, G., Morenate, M., and Zafrilla, J. (2017). How does income redistribution affect households' material footprint? J. Clean. Prod. *153*, 515–527.
27. Golley, J., and Meng, X. (2012). Income inequality and carbon dioxide emissions: the case of Chinese urban households. Energy Econ. *34*, 1864–1872.
28. Hubacek, K., Baiocchi, G., Feng, K., Castillo, R.M., Sun, L., and Xue, J.J.E. (2017). Ecology & environment. Glob. Carbon Inequal. *2*, 361–369.
29. Hubacek, K., Baiocchi, G., Feng, K., and Patwardhan, A. (2017). Poverty eradication in a carbon constrained world. Nat. Commun. *8*, 1–9.
30. Wiedenhofer, D., Guan, D., Liu, Z., Meng, J., Zhang, N., and Wei, Y.-M. (2017). Unequal household carbon footprints in China. Nat. Clim. Change *7*, 75.
31. Shigetomi, Y., Nansai, K., Kagawa, S., and Tohno, S. (2014). Changes in the carbon footprint of Japanese households in an aging society. Environ. Sci. Technol. *48*, 6069–6080.
32. Shigetomi, Y., Matsumoto, K.i., Ogawa, Y., Shiraki, H., Yamamoto, Y., Ochi, Y., and Ehara, T. (2018). Driving forces underlying sub-national carbon dioxide emissions within the household sector and implications for the Paris Agreement targets in Japan. Appl. Energy *228*, 2321–2332.
33. Long, Y., Yoshida, Y., Meng, J., Guan, D., Yao, L., and Zhang, H.J.A.e. (2019). Unequal age-based household emission and its monthly variation embodied in energy consumption—a case study of Tokyo. Japan *247*, 350–362.
34. Abdul-Manan, A.F.N. (2015). Uncertainty and differences in GHG emissions between electric and conventional gasoline vehicles with implications for transport policy making. Energy Policy *87*, 1–7.
35. Grischkat, S., Hunecke, M., Böhler, S., and Haustein, S. (2014). Potential for the reduction of greenhouse gas emissions through the use of mobility services. Transp. Policy *35*, 295–303.
36. Saner, D., Heeren, N., Jäggi, B., Waraich, R.A., and Hellweg, S. (2013). Housing and mobility demands of individual households and their life cycle assessment. Environ. Sci. Technol. *47*, 5988–5997.
37. O'Neill, D.W., Fanning, A.L., Lamb, W.F., and Steinberger, J.K. (2018). A good life for all within planetary boundaries. Nat. Sustain. *1*, 88–95.
38. Vita, G., Ivanova, D., Dumitru, A., García-Mira, R., Carrus, G., Stadler, K., Krause, K., Wood, R., and Hertwich, E.G. (2020). Happier with less? Members of European environmental grassroots initiatives reconcile lower carbon footprints with higher life satisfaction and income increases. Energy Res. Soc. Sci. *60*, 101329.
39. Capstick, S., Lorenzoni, I., Corner, A., and Whitmarsh, L. (2014). Prospects for radical emissions reduction through behavior and lifestyle change. Carbon Mange. *5*, 429–445.
40. Dubois, G., Sovacool, B., Aall, C., Nilsson, M., Barbier, C., Herrmann, A., Bruyère, S., Andersson, C., Skold, B., Nadaud, F., et al. (2019). It starts at home? Climate policies targeting household consumption and behavioral decisions are key to low-carbon futures. Energy Res. Soc. Sci. *52*, 144–158.
41. Bates, A.E., Primack, R.B., Moraga, P., and Duarte, C.M. (2020). COVID-19 pandemic and associated lockdown as a "Global Human Confinement Experiment" to investigate biodiversity conservation. Biol. Conserv. *248*, 108665.
42. Normile, D. (2020). Japan ends its COVID-19 state of emergency. Science. https://doi.org/10.1126/science.abd0092.
43. Statistics Bureau, Ministry of Internal Affairs and Communications, Japan (2020). Statistical handbook of Japan 2019. http://www.stat.go.jp/english/data/handbook/pdf/2019all.pdf.
44. Gillingham, K.T., Knittel, C.R., Li, J., Ovaere, M., and Reguant, M. (2020). The short-run and long-run effects of COVID-19 on energy and the environment. Joule *4*, 1337–1341.
45. He, G., Pan, Y., and Tanaka, T. (2020). The short-term impacts of COVID-19 lockdown on urban air pollution in China. Nat. Sustain *3*, 1005–1011.
46. Forster, P.M., Forster, H.I., Evans, M.J., Gidden, M.J., Jones, C.D., Keller, C.A., Lamboll, R.D., Quéré, C.L., Rogelj, J., Rosen, D., et al. (2020). Current and future global climate impacts resulting from COVID-19. Nat. Clim. Change *10*, 913–919.
47. Huang, X., Ding, A., Gao, J., Zheng, B., Zhou, D., Qi, X., Tang, R., Wang, J., Ren, C., and Nie, W. (2020). Enhanced secondary pollution offset reduction of primary emissions during COVID-19 lockdown in China. Nat. Sci. Rev. *8*, nwaa137.
48. Venter, Z.S., Aunan, K., Chowdhury, S., and Lelieveld, J. (2020). COVID-19 lockdowns cause global air pollution declines. Proc. Natl. Sci. Acad. Sci. USA *117*, 18984–18990.
49. Huang, Y., Shigetomi, Y., Chapman, A., and Matsumoto, K. (2019). Uncovering household carbon footprint drivers in an aging, shrinking society. Energies *12*, 3745.
50. Ministry of the Environment, Government of Japan (2017). Annual report on environmental statistics. https://www.env.go.jp/en/statistics/.
51. Chen, C.-f., de Rubens, G.Z., Xu, X., and Li, J. (2020). Coronavirus comes home? Energy use, home energy management, and the social-psychological factors of COVID-19. Energy Res. Soc. Sci. *68*, 101688.
52. Food and Agriculture Organization of the United Nations (2020). FAOSTAT: food and agriculture data. http://www.fao.org/faostat/en/.
53. Schellnhuber, H.-J., van der Hoeven, M., Bastioli, C., Ekins, P., Jaczewska, B., Kux, B., Thimann, C., Tubiana, L., Wanngård, K., and Slob, A. (2018). Final report of the High-Level Panel of the European Decarbonisation Pathways Initiative. https://ec.europa.eu/info/publica

tions/final-report-high-level-panel-european-decarbonisation-pathways-initiative_en.

54. Long, Y., Yoshida, Y., Zhang, R., Sun, L., and Dou, Y. (2018). Policy implications from revealing consumption-based carbon footprint of major economic sectors in Japan. Energy Policy *119*, 339–348.
55. Lai, K.Y., Webster, C., Kumari, S., and Sarkar, C. (2020). The nature of cities and the COVID-19 pandemic. Curr. Opin. Environ. Sustain. *46*, 27–31.

[56]. Mackenzie, S.H., and Goodnow, J. (2020). Adventure in the age of COVID-19: embracing microadventures and locavism in a post-pandemic world. Leis. Sci. https://doi.org/10.1080/01490400.2020.1773984.

57. Cho, E. (2020). Examining boundaries to understand the impact of COVID-19 on vocational behaviors. J. Vocational Behav. *119*, 103437.
58. Lenzen, M., Wood, R., and Wiedmann, T. (2010). Uncertainty analysis for multi-region input–output models—a case study of the UK's carbon footprint. Econ. Syst. Res. *22*, 43–63.
59. Wiedmann, T., Lenzen, M., Turner, K., and Barrett, J. (2007). Examining the global environmental impact of regional consumption activities—Part 2: review of input–output models for the assessment of environmental impacts embodied in trade. Ecol. Econ. *61*, 15–26.
60. Lenzen, M., Murray, S.A., Korte, B., and Dey, C.J. (2003). Environmental impact assessment including indirect effects—a case study using input–output analysis. Environ. Impact Assess. Rev. *23*, 263–282.
61. Lenzen, M. (1998). Primary energy and greenhouse gases embodied in Australian final consumption: an input–output analysis. Energy policy *26*, 495–506.
62. Wiedmann, T., and Lenzen, M. (2018). Environmental and social footprints of international trade. Nat. Geosci. *11*, 314–321.
63. Long, Y., Dong, L., Yoshida, Y., and Li, Z. (2018). Evaluation of energy-related household carbon footprints in metropolitan areas of Japan. Ecol. Model. *377*, 16–25.
64. Shigetomi, Y., Nansai, K., Kagawa, S., and Tohno, S. (2015). Trends in Japanese households' critical-metals material footprints. Ecol. Econ. *119*, 118–126.
65. Leontief, W.W. (1936). Quantitative input and output relations in the economic systems of the United States. Rev. Econ. Stat. *18*, 105–125.
66. Leontief, W. (1970). Environmental repercussions and the economic structure: an input-output approach. Rev. Econ. Stat. *52*, 262–271.
67. Su, B., and Ang, B.W. (2015). Multiplicative decomposition of aggregate carbon intensity change using input–output analysis. Appl. Energy *154*, 13–20.
68. Ministry of Internal Affairs and Communications (2016). 2011 input-output tables for Japan. https://www.soumu.go.jp/english/dgpp_ss/data/io/io11.htm.
69. Agency for Natural Resources and Energy (2017). FY2016 Annual Report on Energy (Energy White Paper). https://www.enecho.meti.go.jp/en/category/whitepaper/.
70. Long, Y., Yoshida, Y., Zhang, H., Zheng, H., Shan, Y., and Guan, D. (2020). Japan prefectural emission accounts and socioeconomic data 2007 to 2015. Sci. Data *7*, 1–8.
71. Statistics Bureau of Japan. FIES Family Income and Expenditure Survey, (Ministry of Internal Affairs and Communications). https://www.stat.go.jp/english/data/kakei/index.html
72. Nansai, K., Kagawa, S., Kondo, Y., Suh, S., Inaba, R., and Nakajima, K. (2009). Improving the completeness of product carbon footprints using a global link input–output model: the case of Japan. Econ. Syst. Res. *21*, 267–290.
73. Nansai, K., Kondo, Y., Kagawa, S., Suh, S., Nakajima, K., Inaba, R., and Tohno, S. (2012). Estimates of embodied global energy and air-emission intensities of Japanese products for building a Japanese input-output life cycle assessment database with a global system boundary. Environ. Sci. Technol. *46*, 9146–9154.
74. The World Bank. Inflation, consumer prices (annual %). https://data.worldbank.org/indicator/FP.CPI.TOTL.ZG.
75. Statistics Bureau of Japan (2020). Report on the Consumer Price Index. https://www.stat.go.jp/english/data/cpi/index.html.
76. Lee, J., Taherzadeh, O., and Kanemoto, K. (2021). The scale and drivers of carbon footprints in households, cities and regions across India. Glob. Environ. Change *66*, 102205.
77. Kawajiri, K., Ihara, T., Hatayama, H., and Tahara, K. (2018). Revealing hidden CO_2 impacts from consequential consumption by matrix analysis: application to Japanese single households. J. Clean. Prod. *172*, 582–590.
78. National Institute of Population and Social Security Research (2014). Household projections for Japan 2010-2035: outline of results and methods. http://www.ipss.go.jp/pp-ajsetai/e/hhprj2013/t-page_e.asp.
79. Nansai, K., Fry, J., Malik, A., Takayanagi, W., and Kondo, N. (2020). Carbon footprint of Japanese health care services from 2011 to 2015. Resour. Conserv. Recycl. *152*, 104525.
80. Mi, Z., Meng, J., Guan, D., Shan, Y., Song, M., Wei, Y.-M., Liu, Z., and Hubacek, K. (2017). Chinese CO_2 emission flows have reversed since the global financial crisis. Nat. Commun. *8*, 1712.