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

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Rapid and large-scale changes in household consumption patterns during the COVID-19 pandemic can serve as a natural experiment to explore 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 included moderate confinement measures. COVID-19 confinement measures in Japan, and associated lifestyle change, 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, with carbon footprint increasing for some (e.g. eating at home), while declining (e.g. eating out, transportation, clothing, entertainment) or remaining relatively unchanged for others (e.g. housing). 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.

Keywords: Decarbonization, Input-output analysis, Greenhouse gas emissions, Natural experiment

INTRODUCTION

The coronavirus disease 2019 (COVID-19) emerged in the 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 tele-commuting, scaling down (or even halting) of economic activity (e.g. services, 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 a second and third wave 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[62]. For example, studies have estimated substantial short-term decreases in Greenhouse Gases (GHGs) emissions[6,7] nationally and globally, as well as locally in some emission hotspots[8-11]. 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[12,13,37]. Furthermore, many of the actual environmental outcomes seem to vary substantially between countries, depending on their different approaches to containment measures[14-15]. Most of the studies mentioned above have explored the environmental outcomes of the COVID-19 pandemic through measuring directly environmental variables or identifying macro-level patterns associated with changes in aggregate economic and social activity. It can thus be argued that they 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 exploring quantitatively 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/households, their consumption choices and impact on the environment[16,17], e.g. carbon footprints of current and future lifestyles in the UK[18], USA[19], China[20,21], and Japan[22], among others. Other studies have identified the very diverse factors mediating the environmental impacts of lifestyles and consumption practices such as household type[23], income/wealth (and related inequalities)[24-28], and demographic processes (e.g. aging)[29-31].

At the same time it has been argued that by 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[29,32-34,17,35]. For example studies have pointed to the environmental dividends that a voluntary “downsizing” of the lifestyle has, without necessarily compromising the quality of life[36,37]. 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, dietary transitions)[38].

Conversely most studies exploring the environmental outcomes of large-scale lifestyle changes have either relied on simulations or long-term historical data[39].

Based on 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[40], 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. Global Human Confinement Experiment)[40] that can provide profound insights about the environmental outcomes of large-scale changes in human activity due to its extensive and rapid effects on socioeconomic activity and human behavior[40] (Anthropause).

This study focuses on Japan, which offers an ideal setting in terms of its significant contribution to anthropogenic climate change, its distinct demographic/socioeconomic characteristics, and its response to the outbreak using much milder control policies compared to other countries. On the one hand, Japan is the world's 3rd largest economy and 5th largest GHG emitter, with 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 and strict lockdown, instead influencing the restriction of usual behavior through mild measures[41]. This makes Japan arguably a better proxy of a more "reduced activity" lifestyle compared to most other developed countries that endured more severe measures. Furthermore, Japan has been undergoing profound demographic changes in terms of aging, with the proportion of persons >65 years old increasing from 10% in 1985 to 28.1% in 2018 (one of the highest such fractions in the world)[42]. This makes Japan an ideal setting to explore the age-differentiated environmental outcomes of lifestyle change, considering the observed trends towards higher affluence, consumerism, and population ageing in many parts of the developed and developing world[17].

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

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 to 2015-2019 levels (green/yellow areas), and the major constituent of each consumption component for 2020 (pie charts). Overall, the results suggest that the total carbon footprint has not changed throughout the period of January-May 2020 compared to the five previous years (2015-2019). Indeed, the total monthly carbon footprint for 2020 (red line) has remained with 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 decreased slightly the carbon footprint for the months of April and May considering that it reaches the upper bound of the 2015-2019 carbon footprints for these months.

<<Insert Figure 1 here >>

When looking at the disaggregated carbon footprint for individual consumption categories, as expected, there are large overall the carbon footprint 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 eating at home increased substantially (**Figure 1A-H)**. For all these consumption categories the footprint changes from 2015-2019 levels are 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, through not reaching the levels of previous year.

The total transport-related emissions (both direct and indirect) followed similar trajectories as the five years before the outbreak (albeit a bit elevated in January-February), but fell well below the levels of previous years during April and May, when the confinement measures affected travelling patterns for large segments of the population (**Figure 1Q**). This decline is mainly due to decreases in gasoline consumption for private vehicles, which fell 18% below the lowest emission levels of the five previous years. This seems to imply that even without mandatory control measures, Japanese residents decreased substantially their private vehicle using 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 five years with some small exceptions (**Figure 1K-N)**. Albeit 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 the decreasing demand for space heating due to the regular seasonal warming from March have weekended the COVID-19' impact on housing related emission, rather than any unusually high temperatures compared to previous years (**Figure S2**, Supplementary Material). The carbon footprint of other household consumption categories such as medical services and education, were close to past footprint levels, with the former staying at the higher end of the spectrum and the latter at the lower end of the spectrum (**Figure 1P, R)**.

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 compared to previous years, with some signs of slight increase. However, there were very pronounced and changes in the carbon footprints of some consumption sub-component, 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.

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<<Insert Figure 3 here >>

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Age-differentiated carbon footprints.

Figure 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 reduced very significantly in the subsequent months across all age groups.

Second, the age-differentiated carbon footprints for housing and related energy use (**Figure 2A-D**) seem 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 are from electricity and natural gas (**Figure 3**), which might explain the increase by age in **Figure 2D**. When looking in more detail energy use patterns (**Figure 2B-D, Figure 3**), as temperature increases into the spring season, heating demand decreases appreciably. Interestingly, emissions linked to sewage show a slight increase in April 2020 among age groups >45 years old compared to previous years, but it is not clear why this happens. While it could be due to increased hand washing for sanitary purposes, the lower than average sewage emission in May for all groups might challenge this hypothesis.

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

When looking more closely into 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. While it is possible that some of the increase 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 (**Figure 4A, F**), there have also been very visible increases during April-May 2020 from more perishable items such as red meat, eggs and dairy, and fresh vegetables and fruit (**Figure 4C-E**). There is a marked and consistent increase in the carbon footprint of eating at home across all age groups, with the April 2020 levels being consistently higher than the highest related footprint of the past five years. In contrast, there are exactly the opposite consistent patterns for the carbon footprint of eating out (**Figure 4B**). However, we have to point that we cannot infer through these results whether dietary change took place during the confinement measures, and its effect on GHG emissions. This is because all of the distinct food categories in **Figure 4** relate to eating in, as in the FIES survey expenses for “eating in” is divided across food item categories. However, in the FIES survey “eating out” is captured as a single block expense category not differentiated by food item. In other words, the results of **Figure 4** should not be used to elicit whether dietary change occurred, and the associated changes in emissions.

Finally, when looking more closely 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/order for the aggregate footprint and almost all individual consumption categories, except for transportation demand. This suggests that no age group altered disproportionally its behavior during the period of confinement measures, when compared to behavior in previous years, and only the younger household cannot wait for going out in May but the elderly generation still lead 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[8,43-46,62].

This suggests the rather different trajectory of GHG emissions patterns from the household sector, compared to 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 due to reduced household consumption influenced from a possible economic downturn on the aftermath of the COVID-19 outbreak[47].

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 (**Figure 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 and the year (e.g. pandemic vs. regular year). This generally higher emissions of elderly households has been pointed in other studies in Japan[29,31,48], and is mainly due to due to higher heat needs and cooking[49]. In our case, the transport-related emissions of elderly households remain low level even after the emergency declaration in May, while the total footprint is not significantly affected as neither emissions from electricity and food consumption show a substantial decline compared to 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 seem to be a substantial variation in carbon footprint patterns among consumption categories, with the main observed carbon footprint trade-offs observed between consumption categories associated with eating at 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 affected substantially the carbon footprint of housing, despite the opposite trends being visible in some other developed countries[50].

Despite people spending 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[31]. Heating and cooling are the largest contributors of housing-related emissions in Japan[31], but the mild weather during late spring in Japan reduces the need for both heating and cooling, as it is also quite evident in past footprint patterns for these categories (**Figure 1K-M**). It is worth mentioning that the 2020 spring period did not experience any abnormal warming, with the average temperatures being rather similar to past years (**Figure S2**, Supplementary Material). However, we cannot preclude that a "reduced activity" lifestyle could increase housing-related carbon footprint during the winter or summer due to the higher demand for heating and cooling respectively.

The most pronounced carbon footprint shifts are linked to changes in eating habits, and 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, with these changes being 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 of the carbon footprint of emission-intensive food categories such as red meat, dairy and eggs[39], 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[51].

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, as the confinement measures were rather moderate and largely voluntary[41]. Thus, compared to other countries they could in theory reflect better 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 lower 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[8,43-46,62], there seem 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 when seeking to contribute to decarbonization through lifestyle change, in that environmental benefits might not materialize simply by 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[36,37]. 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[17,39,52] , 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 using.

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 Limitations in Methods). The former would require the development of multi-regional input-output (MRIO) tables that have high sectoral resolution and employ recent datasets that can capture well national economic structure, going beyond simple calculations based on GDP change. This is to our best knowledge a major research gap for Japan, with most current studies unable to use such high-resolution MRIOs[22,53]. The latter would possibly require dedicated primary data collection campaigns from nationally representative singe-person households, as these are not considered in the underlying consumption datasets collected by the Japanese government and used in this study (see Methods).

More broadly 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 compared to other developed countries, which in our mind make them a better approximation of "reduced activity" lifestyles. However, comparative studies across different countries could provide a better micro-level evidence of how the "Anthroposause" has affected the environment, which would complement better the emerging studies from the macro-level[54-56].

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 at 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 (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_d^i) and indirect emissions (E_{cf}^i) (Eq.1).

$$E^i = E_d^i + E_{cf}^i \tag{1}$$

In this study we estimate the total carbon footprint of household consumption for the period 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, HFCs, PFCs, 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[57-61]. Indirect emissions can be estimated through Environmental Extended Input-output (EEIO) analysis[29,53,62-64], which involves the use of an economic input-output table (IO-T). IO-Ts have been 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):

$$\boldsymbol{X} = (\mathbf{I} - \boldsymbol{A})^{-1}\boldsymbol{F} \tag{2}$$

…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 using 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):

$$\boldsymbol{X} = (\mathbf{I} - \boldsymbol{A}^d)^{-\mathbf{1}}\boldsymbol{F}^d \tag{3}$$

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

$$E_{cf}^i = \sum_{j=1} e_j^i * \left(\mathbf{I} - \boldsymbol{A}^{\mathbf{d}}\right)^{-1} * Ep^i \tag{4}$$

…where E_{cf}^{i} indicates the household carbon footprint by consumption item i; Ep^{i} refers to monetary consumption on consumption item i; e_{j}^{i} 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. $\sum_{j=1} e_{j}^{i} * \left(\mathbf{I} - \boldsymbol{A}^{\mathbf{d}}\right)^{-1}$ 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, while kerosene is an important fuel for space heating especially in the mountainous regions[49].The direct emission is estimated through Equation (5),

$$E_{y,m}^{dr} = \sum_{i=1} e_{t}^{i} * Ep_{y,m}^{i} * Upc_{y,m}^{i} \quad (5)$$

…*where* $E_{y,m}^{dr}$ indicates the total direct household emissions in year y month m, Ep^{i} the direct monetary on fuel i, $Upc_{y,m}^{i}$ the unit price of fuel i in year y month m, and e_{t}^{i} the emission intensity of fuel i in year y derived from hthe Agency for Natural Resources and Energy by year[69,70].

To analyze 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 emissions are merged with other transportation-related indirect emission into the "Transportation and communication" sector, city gas and LPG in gas-related emissions with indirect up-stream emission, and kerosene into the "Other heating and lighting" sector.

Datasets and Input-Output Tables

The base data for household consumption used to calculate the indirect and direct emissions comes from the monthly Family Income and Expenditure Survey (FIES)[71], conducted monthly across Japan by the Statistics Bureau, 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 comes from the Embodied Energy and Emission Intensity Data for Japan Using Input-Output Tables (3EID), a database of Japan's sectoral intensity of life-cycle environmental burdens. This is constructed from the Input-Output Tables for Japan using a EEIO model developed by Nansai et al (2002)[72,73]. Even though the original model was developed in 2002, it is updated regularly based on the Japan official input-output table. 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 multi-regional input-output (MRIO) table for two reasons: (a) higher sectoral resolution; (b) most recent data availability. In more detail, the 3EID has a much higher sectoral resolution (390 sectors) when compared with other MRIOs such as WIOD (56 sectors) and EXIOBASE (200 sectors), which is closer to the structure of the FIES that 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 corresponding between categories between model and data (see below). Furthermore, the 3EID model has more recent data availability compared to other SRIOs with similar sectoral resolution such as Eora (401 commodities). In particular while both 3EID and Eora produce recent data, the latter produces data that is an extension of estimates based on GDP and other information. Thus, it does not reflect the latest Input-Output table 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, as the classification of industries in the 3EID database differs from the classification of consumption elements in the FIES expenditure data. We matched the data following the general approach outlined in Jiang et al. (2020)[22], as shown in Table S1 (Supplementary Material) that 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 the 3EID and the 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 have 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 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 is 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, Supplementary Material for 2020 levels). To understand convergences and divergences with past emission patterns, we compare each footprint elements 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, with no unnatural peaks or declines in the study period compared to previous years (**Figure S3-S5**, Supplementary Material).

Methodological limitations

Despite the high resolution of consumption categories and data quality, this study has three main limitations, namely (a) the inability to apply distinct carbon intensities for imported goods, (b) an inability to capture single-person households, (c) 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 to our results. As outlined above, despite the higher sectoral resolution and data quality expected by adopting the 3EID model, this omission might underestimate the actual carbon footprint, as goods imported in the domestic market tend to have longer value chains, and thus higher GHG emissions when compared to similar domestic goods[76]. However, apart from the Global Link Input-output for 2005[73], to the best of our knowledge no input-output table 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 remains a broader gap in the literature in recent decades.

Second, the underlying FIES datasets used in this study do not capture single-person households, as the most recent sample used in this study only contains 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 (see also Results). 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 is the actual effect of this omission from our calculations, in terms of overestimation, underestimation or balancing out. Thus, considering the relatively large prevalence of single-person households in the Japanese society[78], some caution should be exerted when generalizing the results of the analysis.

Third, considering that 3EID data is for 2015 it might be that technology effects might lead to the over- or under-estimation of the carbon footprints when applied for other years[73,79]. Still we believe that these changes might be relatively marginal considering that the technology improvement needs a comparatively longer time to manifest[80]. One interesting phenomenon might be the effect of COVID-19 in production and trade chains, considering 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 in reality to be marginal as the confinement measures 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 lives such as starchy and processed food) will not have been affected by any changes in production value chains due to existing stocks.

Figure Legends

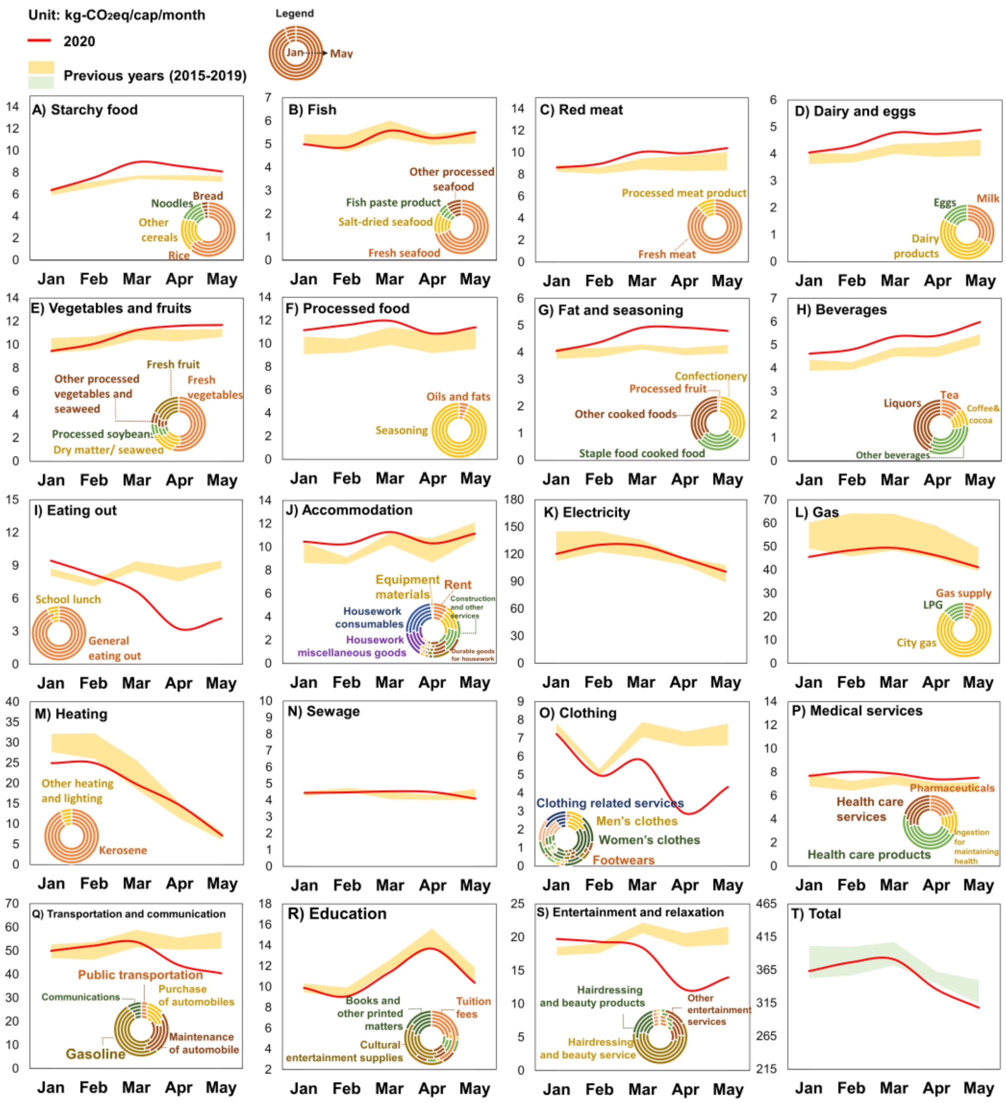
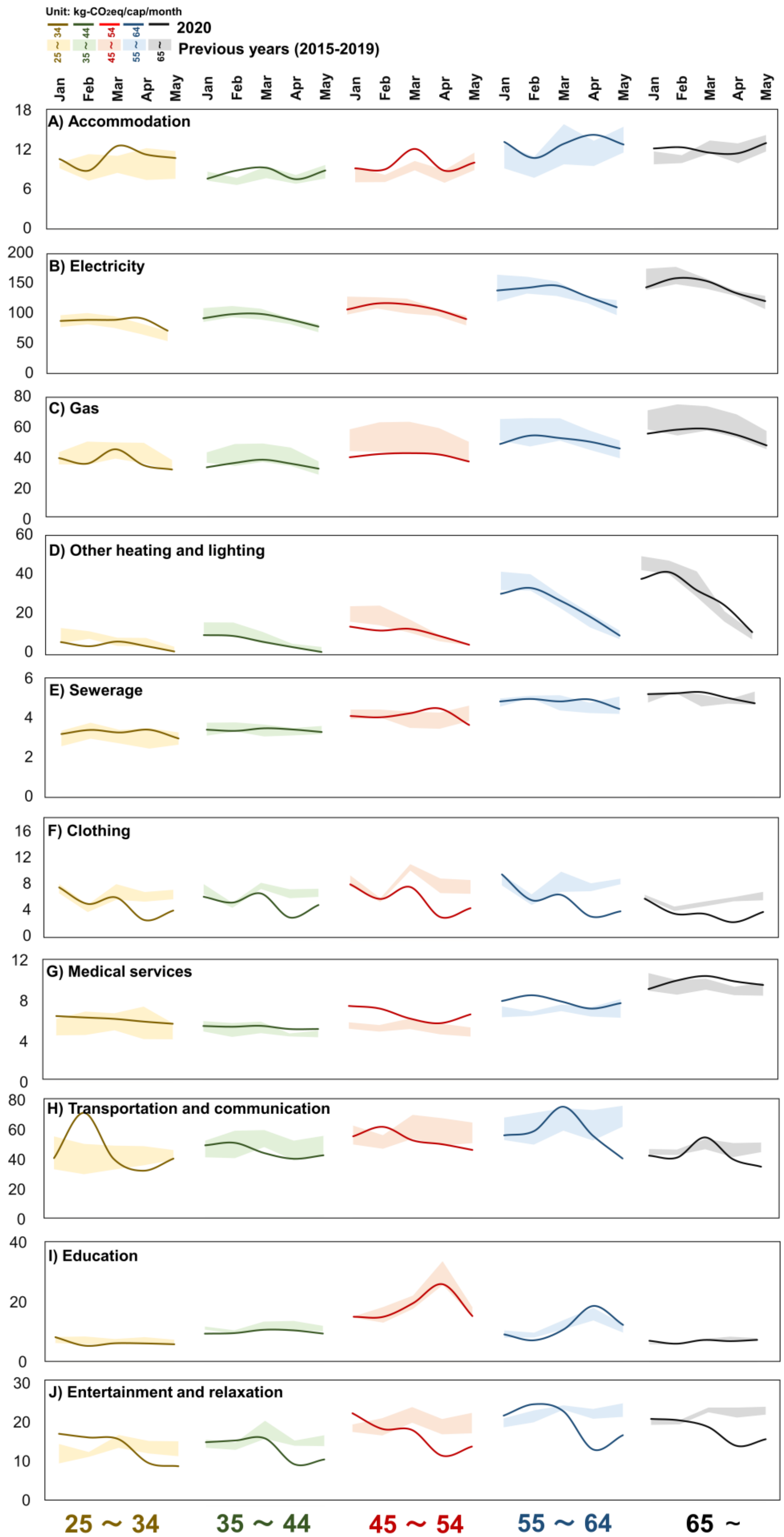


Fig.1 Total carbon footprint of household consumption (in kg-CO_2eq/cap)**.** The red line indicates the 2020 GHG emissions for the different household consumption categories for each corresponding month. The yellow and green areas indicate the emissions ranges for the past five years (2015-2019). Pie charts indicate the main emission sources for each consumption category.


Unit: kg-CO2eq/cap/month
2020
Previous years (2015-2019)
A) Accommodation
B) Electricity
C) Gas
D) Other heating and lighting
E) Sewerage
F) Clothing
G) Medical services
H) Transportation and communication
I) Education
J) Entertainment and relaxation
Jan Feb Mar Apr May
25 ~ 34
35 ~ 44
45 ~ 54
55 ~ 64
65 ~

653

Fig.2 Carbon footprint of non-food consumption categories disaggregated by age group (in kg-CO_2eq/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 five years (2015-2019).

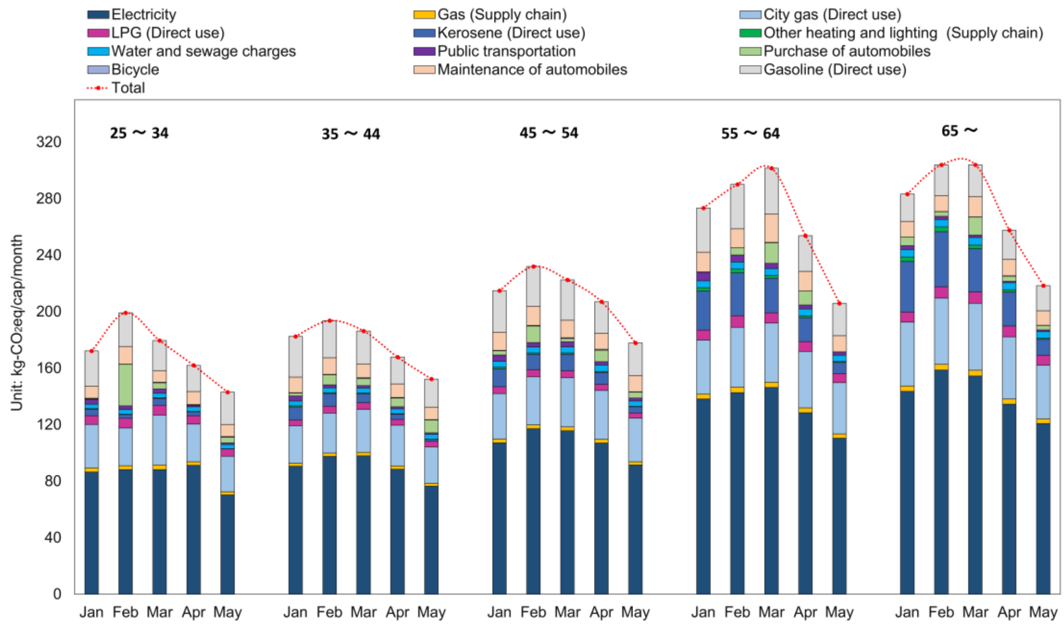


Fig.3 Carbon footprint components for housing, sewage and transportation by age group (in kg-CO_2eq/cap)**.**

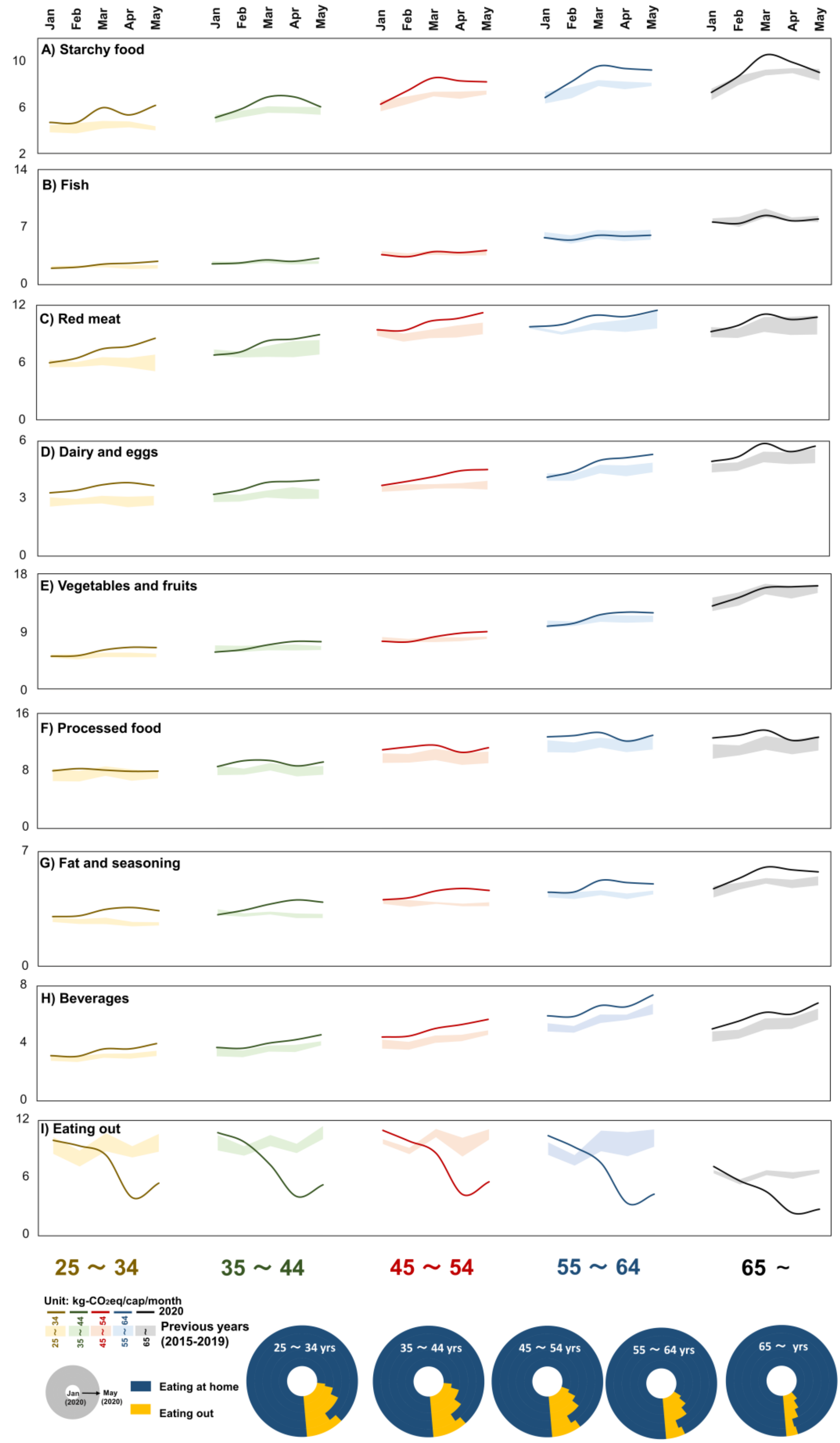


Fig.4 Carbon footprint of food consumption categories disaggregated by age groups (in kg-CO_2eq/cap)**.** The lines indicate the 2020 GHG emissions for

the different food-related household consumption categories for each corresponding month. The shades indicate the emission ranges for the past five 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 starting from January (inner circles) to May (outer circles).

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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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