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Carbon footprint of Japanese health care services from 2011 to 2015

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ABSTRACT

The carbon footprint of Japanese health care services, i.e. the domestic greenhouse gas (GHG) emissions caused by health care expenditures, including the associated fixed capital, were calculated using input-output analysis. In 2011 the total carbon footprint of these services was 62.5×10^6 metric tons of CO_2 equivalent ($MtCO_2e$), which is 4.6% of total domestic GHG emissions. Medical services involving hospitalization accounted for the greatest share, at 15.7 $MtCO_2e$. The second highest category, Medical services without hospitalization, accounted for only slightly less: 14.2 $MtCO_2e$. However, the difference in emissions per patient between these two categories was considerable. On average, emissions per patient for Medical services (hospitalization) were 12 tCO_2e/patient, whereas for Medical services (non-hospitalization) they were only 2.1 tCO_2e/patient, or 5.4 times less. In terms of type of medical condition, the greatest annual emissions were associated with cardiovascular disease (6.2 $MtCO_2e$) and neoplasm (4.0 $MtCO_2e$). In terms of age, emissions attributed to patients aged 65 and over accounted for more than half of total health care emissions. By 2015, the total carbon footprint had increased to 72.0 $MtCO_2e$, a rise of over 15% in four years. Although medical care and pharmaceuticals are the main factors responsible for this increase, emissions associated with nursing services have also risen, suggesting that demographic aging may be having a significant impact on GHG emissions. As a countermeasure, the potential annual GHG mitigation achievable through avoidance of unused prescribed medicines resulting in waste was estimated at 1.24 $MtCO_2e$, comparable with the total carbon footprint of home medicines. To safeguard planetary health, in addition to implementing technological improvements to the supply chains of health care services, it will be necessary to provide citizens further options for achieving health promotion and GHG mitigation simultaneously.

1. Introduction

In 2016 the world's population exceeded 7.44 billion (World Bank, 2019b) and average life expectancy reached 72.04 years (World Bank, 2019a). Since 2000, in just 16 years, there has been an increase in global population of 1.32 billion and 4.36 years in life expectancy. In OECD countries, particularly, there is a strong correlation between average life expectancy and per capita health care expenditure (OECD, 2017). In light of this, it can be deduced that achieving Goal 3 of the 17 Sustainable Development Goals (SDGs) (United Nations, 2015) adopted by the U.N. in 2015 ("Ensure healthy lives and promote well-being for all at all ages"), will inevitably require increased spending on health care in the coming years.

Whilst increased spending translates directly to an increase in average life expectancy (OECD, 2017), consideration also needs to be given to the negative consequences. For example, total health care expenditure in the OECD rose from 3375 billion USD in 2000 to 6000 billion USD in 2017, based on 2010 purchasing power parity rates (OECD, 2018). As a percentage of GDP, these statistics represent a rise from 7.2% to 8.8% (OECD, 2018), which means that health care is a significant cost to the economy of these countries. In addition to the economic and social costs of increased spending, the question arises: what are the environmental costs of health care spending? This question highlights the need for a holistic, ecological economics perspective in which the environmental, social and economic impacts of health care spending are analyzed. To this end, in recent years the concept of "planetary health" (Taylor and Mackie, 2017; Whitmee et al., 2015) has come to prominence, stressing the need to foster "co-benefits", viz. enhancing global public health and at the same time protecting the natural systems on which humanity depends. In the context of

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"planetary health" and "environmental sustainability" there is a need to comprehensively quantify the negative environmental impacts of increased health care spending. In particular, it has been previously shown that monetary spending on provision of goods and services for health care services (e.g. purchase of medical equipment) has an associated environmental footprint (Malik et al., 2018). These findings have highlighted the need to quantify the environmental impacts arising in the supply chains driven by health care expenditure. In light of the potential impacts on SDG Goal 13 ("Take urgent action to combat climate change and its impacts") and on the Paris Agreement adopted in 2015 at the 21st U.N. Conference of the Parties (COP21), the relationship between health care spending and greenhouse gas (GHG) emissions has therefore been investigated in a number of countries.

Specifically, in Australia (Malik et al., 2018), the GHG emissions directly and indirectly generated by health care spending, i.e. the carbon footprint of health care, accounted for 7% of the country's GHG emissions in 2014. The corresponding figure for both the U.K. (Sustainable Development Unit, 2016) and Canada (Eckelman et al., 2018) was 5% in 2015. In the U.S., the world's biggest spender on health care, 8 and 10% of national GHG emissions were attributable to health care activities in 2007 (Chung and Meltzer, 2009) and in 2013 (Eckelman and Sherman, 2016), respectively. Although it is not easy to intuitively conceive the relationship between health care and GHG emissions, these studies definitively show that the carbon footprint of health care is significant enough to be considered in national GHG management plans.

The recent health care study (Pichler et al., 2019) using multi-regional input-output analysis (MRIO) compares the global CO_2 emissions induced by health care expenditures of 36 countries, including Japan in 2014. The authors only consider CO_2 emissions, and not a range of greenhouse gases. In comparison with existing studies, such as that of Australia (Malik et al., 2018), the results presented by the global study are different, largely due to a) variations in the consideration of greenhouse gases for the assessment; and b) the use of a range of different data-sets for carrying out the assessment. No detailed comparison with a Japanese case exists, since exists no recent footprint study of Japanese health care.

In 2016 average life expectancy in Japan (83.98 years) was the third highest in the world (World Bank, 2019a), behind only that of San Marino (85.42) and Hong Kong (84.23). The World Health Organization (WHO) also reported that the Healthy Life Expectancy (or HALE, effectively a "disability-free life expectancy") of Japan in 2016 was 74.81 years, a figure that was slightly lower than that for the frontrunner Singapore (76.17). Furthermore, in terms of total health care expenditure in 2017 (OECD, 2018), Japan ranked third (520 billion USD), just below the U.S. and China. In terms of per-GDP expenditure (10.75% of 520 billion USD), Japan ranks sixth highest in the world. This proportion has increased steadily from 5.76% in 1990 to 7.15% in 2000 and 10.9% in 2015.

Regarding the carbon footprint of health care in Japan, several earlier studies calculated the global carbon footprint of the subset "medical services" using the 2005 input-output tables (Nansai et al., 2012a,b) and projected its growth by considering future demographic changes (Shigetomi et al., 2014). Specifically, given that Japan's population will continue to age, it was estimated that by 2035 global GHG emissions arising from medical services will increase by approximately 9% relative to 2005 levels (Shigetomi et al., 2014). Japan needs to make considerable efforts to meet its emission-reduction commitments under the Paris Agreement (viz. a 26% reduction below FY2013 levels by 2030) (Shigetomi et al., 2018), implying that a decoupling of health care and GHG emissions is essential.

Since 2005, however, the carbon footprint of Japanese medical services has not been quantified, and no carbon footprint of health care other than medical services has been found. Since the Great East Japan Earthquake of March 11, 2011, most of Japan's nuclear power facilities have been shut down and there has consequently been a marked shift in the power generation fuel mix. Most significantly, the proportion of fossil-fuel power plants, which are far more carbon-intensive than nuclear plants, has increased markedly. Even so, there is no comprehensive quantitative picture of the relationship between health care services and GHG emissions from power generation. Together, these considerations have motivated us to decipher health care supply chains from a carbon footprint perspective in order to identify key actors in the supply chains, with a view to decoupling.

Hence, the objective of this study is to carry out a quantitative comparison of the carbon footprint of Japanese health care using the 2011 national input-output tables, corresponding to the year the earthquake occurred, and the 2015 footprint using the latest tables. The health care services considered are "Medical services", "Health and hygiene" and "Nursing services", including the fixed capital formation required for these services, plus "Household medication". Furthermore, we also aim to characterize the supply chain structure of the respective carbon footprints and identify the carbon footprint of "Medical services" by type of injury and disease.

2. Methods and data

2.1. Carbon footprints estimated by input-output analysis

We set out to compute the GHG emissions associated directly and indirectly with health care demand in Japan by means of an input-output analysis that was similar to analyses employed in previous studies (Eckelman and Sherman, 2016; Eckelman et al., 2018; Malik et al., 2018; Sustainable Development Unit, 2016). Input-output analysis (Lenzen, 1998; Leontief, 1970; Nansai et al., 2003) provides an accounting framework between supply on the production side and demand on the consumption side. This model can be represented by Eq. (1),

$$\mathbf{x} = \mathbf{Zi} + \mathbf{f} \tag{1}$$

where $\mathbf{x} = (x_j)$ is an output vector whose elements are the production output x_j of sector j, the matrix $\mathbf{Z} = (z_{ij})$ is an intermediate transaction matrix comprising elements z_{ij}, representing the volume of trade between sector i and sector j, and $\mathbf{f} = (f_j)$ is the final demand vector, made up of elements f_i, representing the final demand of sector j. The vector i is for summation and all its elements are unity.

If the input coefficient matrix $\mathbf{A} = (a_{ij})$ that expresses the direct input of sector i needed for the per-unit production of sector j is defined as $\mathbf{A} = \mathbf{Z}\hat{\mathbf{x}}^{-1}$, Eq. (1) is transformed into Eq. (2). Then, by solving for $\mathbf{x}$, Eq. (3) can be derived. The ˆ symbol expresses a matrix having its vector elements along the diagonal, and other elements equal to zero.

$$\mathbf{x} = \mathbf{Ax} + \mathbf{f} \tag{2}$$

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{f} = \mathbf{Lf} \tag{3}$$

Here, the matrix $\mathbf{L} = (l_{ij}) = (\mathrm{I} - \mathbf{A})^{-1}$ is a Leontief inverse matrix, and element l_{ij} represents the production volume of sector i directly and indirectly caused by the per-unit production of sector j. Accordingly, if the arbitrary final demand $\mathbf{f}$ (consumption) is input into Eq. (3), it determines the production volume $\mathbf{x}$ of each sector required to satisfy this final demand.

When the matrix $\mathbf{A}$ and the vector $\mathbf{f}$ include imported commodities, the vector $\mathbf{x}$ represents the total production volume of domestic and imported products. In this study, we focus on domestic production only; the flows of imported commodities are excluded from the matrix $\mathbf{A}$ and vector $\mathbf{f}$ by defining the matrix $\mathbf{A}^d = (\mathrm{I} - \hat{\mathbf{m}})\mathbf{A}$ and the vector $\mathbf{f}^d = (\mathrm{I} - \hat{\mathbf{m}})\mathbf{f}$. Thus, Eqs. (2) and (3) are formulated as $\mathbf{x} = \mathbf{A}^d\mathbf{x} + \mathbf{f}^d$ and $\mathbf{x} = (\mathbf{I} - \mathbf{A}^d)^{-1}\mathbf{f}^d = \mathbf{L}^d\mathbf{f}^d$, respectively. Here, each element m_i of the vector $\mathbf{m}$ means the import ratio of commodity i.

Then, we define the vector $\mathbf{d} = (d_i = D_i/\bar{x}_i)$, which comprises elements representing the GHG emissions generated per unit production in each sector. D_i represents the annual GHG emissions from sector i, while $\bar{x}_i$ is the total annual production volume of sector i. The total GHG

Table 1
Five general and 16 fine-scale health care categories in Japan, their carbon footprint per unit expenditure in 2011, and share of emissions from electric power generation in carbon footprint.

Five categories	name	Sixteen categories	name	Activities	Unit carbon footprint (tCO_2e/m-JPY)	Share of emissions from electric power generation (%)
1	Medical services	1	Hospitalization	Medical examination or treatment as an inpatient at a hospital	0.989	36%
1	Medical services	2	Non-hospitalization	Medical examination or treatment as an outpatient at a hospital, preventive health activities, or medical consultation center	0.958	36%
1	Medical services	3	Dentistry	Dental treatment or dental examination at a hospital or dental clinic	0.800	45%
1	Medical services	4	Pharmacy dispensing	Dispensing of pharmaceuticals at a pharmacy or dispensing pharmacy	1.22	27%
1	Medical services	5	Miscellaneous medical services	Maternity clinic, visiting nursing care station, operating theater eye bank, bone marrow bank, hygiene inspection center, medical equipment sterilization, clinical trial	0.982	48%
2	Health and hygiene	6	Non-profit	Public health center, health consultation center, quarantine station, or inspection service of national or local government	1.28	37%
2	Health and hygiene	7	For-profit	Public health center, health consultation center, quarantine station, or inspection service not of national or local government	0.767	45%
3	Nursing care	8	Facility services	Nursing care facility for the elderly	1.23	34%
3	Nursing care	9	Excluding facility services	Home nursing care service, preventive nursing care service	1.22	36%
4	Fixed capital formation	10	Private (for medical services)	Fixed assets, e.g., buildings, machinery, and equipment of private hospitals	1.97	20%
4	Fixed capital formation	11	Public (for medical services)	Fixed assets, e.g., buildings, machinery, and equipment of public hospitals	1.82	20%
4	Fixed capital formation	12	Private (for health and hygiene)	Fixed assets, e.g., buildings, machinery, and equipment for private preventive health	2.20	19%
4	Fixed capital formation	13	Public (for health and hygiene)	Fixed assets, e.g., buildings, machinery, and equipment for public health	1.69	22%
4	Fixed capital formation	14	Private (for nursing care)	Fixed assets, e.g., buildings, machinery, and equipment for private nursing care	2.68	17%
4	Fixed capital formation	15	Public (for nursing care)	Fixed assets, e.g., buildings, machinery, and equipment for public nursing care	2.72	16%
5	Household medication	16	Home medication	Medicine purchased directly by households and offices	1.91	45%

emissions, y, generated by production volume, $\mathbf{x}$, can be expressed as the product of $\mathbf{d}$ and $\mathbf{x}$, as shown in Eq. (4). Also, by determining the production volume, $\mathbf{x}$, induced by domestic final demand, $\mathbf{f}^d$, based on the relationship given by $\mathbf{x}=\mathbf{L}^d\mathbf{f}^d$, we can compute the total GHG emissions (carbon footprint) induced by domestic final demand. Furthermore, we can express $\mathbf{e} = (e_j) = \mathbf{dL}^d$, where e_j is a coefficient that represents the induced domestic GHG emissions per unit production in sector j, often called "embodied emission intensity" or "emission multiplier".

$$y=\mathbf{dx} = \mathbf{dL}^d\mathbf{f}^d = \mathbf{ef}^d \tag{4}$$

In this study, 397 sectors (i and j) were defined using the 2011 Japanese input-output tables (JIOT), which are the most recent data currently available. The carbon footprints of the healthcare-related sectors shown in Table 1 were determined. We also calculated the carbon footprint associated with the fixed capital formation required for health care using the fixed capital matrix, which is attached to the input-output table and describes for each sector the amount of fixed capital formation.

Endogenizing the fixed capital matrix into matrix A is one approach to capture carbon footprint generation via fixed capital formation (Lenzen and Treloar, 2004; Minx et al., 2011; Sodersten et al., 2018; Nansai et al., 2008). However, the present study employed a more straightforward approach to allocating the carbon emissions induced by fixed capital formation to health care categories, namely, multiplying demand for each category by the embodied emission intensity corresponding to that demand.

2.2. Estimated sectoral GHG emissions based on input–output tables

In this study we employed the emissions reported in the Japan National Report of GHGs Inventory (NRI) (GIO, 2019) and allocated these to each sector in the JIOT. This was to ensure correspondence between the total amount of annual GHG emissions by sector, D_i, and Japan's official GHG emissions. The GHGs considered were CO_2, CH_4, N_2O, HFCs, PFCs, SF_6 and NF_3.

The method used for calculating GHGs in the NRI conforms with the calculation guidelines formulated by the Intergovernmental Panel on Climate Change (IPCC) and agreed by the COP. Japan's fossil-fuel-origin CO_2 emissions were calculated based on the Energy Balance Table (EBT) issued by the Agency for Natural Resources and Energy (Japanese Agency for Natural Resources and Energy, 2019). Since EBT shows the flow of fossil fuel input, conversion and consumption per year by industrial category, it allows us to estimate the sectoral CO_2 emissions from fuel combustion in each category. In the NRI, GHG emissions from non-energy sources, such as CO_2 from limestone, are estimated, using emission factors and related activity data provided by the industries responsible, for example. It should be noted that the estimates for energy-derived CO_2, non-energy-derived CO_2, CH_4 and N_2O emissions are all based on financial year, while those for HFCs, PFCs, SF_6 and NF_3 are based on calendar year.

Converting NRI emissions to sectoral emissions in the JIOT presents the following challenges: 1) There are differences between financial year (FY) and calendar year-based values; 2) There are differences in the industrial categories defined by the NRI and the sectors in the JIOT; 3) There are differences in the fuel input quantities specified in the EBT and those in the JIOT; and 4) The presence or absence of international transport (not included in the NRI, but included in the JIOT).

We dealt with these issues as follows. 1) For gases for which NRI provides FY-based figures, we estimated the 2011 value by adding 1/4 of the FY2010 value and 3/4 of the FY2011 value for the gas. 2) We constructed a concordance table that relates the classifications of EBT for energy-derived CO_2 and NRI's categories for other gases to the sectors in the JIOT. When an EBT or NRI classification corresponded to a single sector in the JIOT, we directly applied the fuel-input amount from the EBT and the emissions from the NRI to the sector. If the NRI classification corresponded to multiple sectors in the JIOT, we allocated NRI emissions to sectors based on the amount of activity related to the emission as a fuel input to the sectors, or their production amount, by referring to the "quantity table" – a supplemental table to the JIOT. This describes the physical quantities (weight, mass, etc.) of the commodity inputs into each sector (e.g. petroleum products, coal products, etc.).

However, for this allocation it is necessary to address issue 3), for which there are two discrepancies. The first case is that the EBT describes a fuel input to a specific category, whereas the quantity table shows no input for that fuel in the corresponding sector. Secondly, and conversely, there is a fuel input for a sector in the quantity table, but no fuel input for the corresponding category in the EBT. In this study, we dealt with the first case by employing the fuel input in the EBT for that sector. In the second case, we first adjusted the fuel input in the quantity table so that the total annual consumption given in the EBT and in the quantity table were consistent, then employing this corrected value as the fuel input quantity for the sector in the JIOT. For issue 4), this study focused only on domestic emissions and excluded fuel usage associated with international air transport and international shipping.

Next, fuel consumption for raw materials production was deducted from the fuel input described above, and the CO_2 emissions were calculated by multiplying the fuel consumption for combustion by the calorific value and the CO_2 emissions factor. By summing all emissions for the gases, we then determined the direct GHG emissions by each sector in the JIOT.

2.3. Analyzing the carbon footprints associated with major commodities

In order to understand the structure of the health care carbon footprint, we broke it down from two perspectives (Nakamura and Nansai, 2016). First, we calculated the breakdown matrix $\mathbf{P} = (p_{ij})$ of the carbon footprint defined by Eq. (5), which gives the GHG emissions associated with direct procurement for sector (i) in health care (j). This enabled us to identify which commodities purchased in health care services induce significant GHG emissions. Second, we derived the breakdown matrix $\mathbf{Q} = (q_{ij})$ defined by Eq. (6), which gives the GHG emissions in sector (i) originating from demand for health care (j). This allowed us to detect which sectors are actually associated with major GHG emissions within health care supply chains.

$$\mathbf{P} = (p_{ij}) = \hat{\mathbf{e}}\widehat{\mathbf{A}^d\mathbf{f}^d} \tag{5}$$

$$\mathbf{Q} = (q_{ij}) = \hat{\mathbf{d}}\mathbf{L}^d\hat{\mathbf{f}}^d \tag{6}$$

2.4. Disaggregation of medical services carbon footprint by type of injury and disease

The final demands for "Medical services (hospitalization)" and "Medical services (non-hospitalization)" were each broken down by age (≥65 years and younger) and by 19 medical conditions, using the "National Medical Expenses Statistics" (Japanese Ministry of Health Labour and Welfare, 2019) which were used to determine the total output of each "Medical service". Then, the carbon footprint for each condition was obtained by multiplying the estimated final "demand" of the condition by the embodied emission intensity, e_j, of the respective medical services sector. We also calculated the carbon footprint per patient by dividing the estimated carbon footprint of a condition by the number of patients with the condition, for both "hospitalization" (inpatient) and "non-hospitalization" (outpatient) services.

2.5. Extrapolation of carbon footprints for 2012–2015

At present, no JIOT have been compiled for years later than 2011. However, "extended input-output tables" have been published for 2012 to 2015, making it possible to obtain final demand 2012–2015 for health care based on 2011 prices. The extended input-output tables are estimated by adjusting values of the 2011 JIOT using the rates of change in the prices of goods and services for each year relative to 2011 prices. This study estimated the 2012–2015 carbon footprints by multiplying the final demand for each year (2012–2015) by the adjusted unit carbon footprint, e_j^{year}, of the corresponding sector, which reflects only the changes in the power generation mix relative to 2011, according to Eq. (7):

$$e_j^{year} = e_j^{2011} \times (1 - s_j^{2011}) + e_j^{2011} \times s_j^{2011} \times \frac{c^{year}}{c^{2011}} \quad (7)$$

where e_j^{2011} is the unit carbon footprint for 2011 and s_j^{2011} is the share of the emission from the electricity sector in e_j^{2011} reported in Table 1, which is determined by referring to q_{ij} in Eq. (6). c^{2011} and c^{year} represent the emission factors of power generation ($kgCO_2/kWh$) in 2011 and each year, respectively. For these factors this study used figures of 0.52 for 2011, 0.57 for 2012, 0.58 for 2013, 0.56 for 2014 and 0.55 for 2015 (Japanese Agency for Natural Resources and Energy, 2019).

Since the extended input-output tables do not include a capital formation matrix describing demand for the goods and services necessary for fixed capital formation, however, for time-series comparison we made the assumption that the carbon footprints for the fixed capital of each year changed from those for 2011 in proportion to the final demand for health care in that year.

3. Results

3.1. Carbon footprints of Japanese health care by 16 categories

In 2011 the carbon footprint associated with health care expenditure in Japan was an estimated 62.5 $MtCO_2e$ (million metric tons of CO_2-equivalent), thus accounting for 4.6% of the total national GHG emissions of 1344 $MtCO_2e$. In terms of individual gases, CO_2 accounted for 59.5 $MtCO_2e$ or 95% of the total. The contributions of other gases amounting to over 1% were 0.978 $MtCO_2e$ (1.6%) of N_2O, 0.925 $MtCO_2e$ (1.5%) of HFCs and 0.850 $MtCO_2e$ (1.4%) of CH_4. Table 1 shows the embodied emission intensity (carbon footprint per unit expenditure) for each health care sector. The value of fixed capital formation was calculated by dividing the carbon footprint of the fixed capital formation by total demand for it.

Fig. 1 shows the breakdown of the carbon footprint, with five categories in the inner ring and 16 categories in the outer ring. If health care expenditure is broadly divided into expenditure related to the provision of services and expenditure on fixed capital formation, 53.5 $MtCO_2e$ (86%) is attributable to the former, while the rest, 8.95 $MtCO_2e$ (14%) is attributable to the latter, which is a considerable share. Notably, "Medical services", with 41.5 $MtCO_2e$, dominated health care emissions. As the earlier studies (Nansai et al., 2012a; Shigetomi et al., 2014) on global carbon footprint do not clearly show the domestic carbon footprint, a dedicated calculation using the original data of those studies was made that estimated the domestic emissions induced by medical services at 45.9 $MtCO_2e$ in 2005 (Nansai, 2019). From 2005–2011, domestic final demand for "Medical services" increased by 1.14%. Over the same period, however, the unit carbon footprint of "Medical services" decreased by about 23% (from 1.3 tCO_2e/m-JPY in 2005 to 1.0 tCO_2e/m-JPY in 2011), when 2005 prices are converted to 2011 prices using the linked input-output tables (Japanese Ministry of Internal Affairs and Communications, 2016). This change in unit carbon footprint can be explained mainly by a reduction in on-site emissions (from 9.1 $MtCO_2e$ in 2005 to 5.6 $MtCO_2e$ in 2011) and electricity consumption (from 389 billion JPY in 2005 to 239 billion JPY in 2011) associated with medical services. Together, these factors canceled out the emissions growth due to the increased unit carbon footprint of electricity (from 25.4 tCO_2e/m-JPY in 2005 to 33.3 tCO_2e/m-JPY in 2011) after the earthquake.

Considering the 16 expenditure categories in more detail, "Medical services (hospitalization)" was the biggest GHG contributor at 15.7 $MtCO_2e$ of emissions, closely followed by "Medical services (non-hospitalization)" at 14.2 $MtCO_2e$; together, these two categories account for 47.8% of the total. Although the GHGs emitted on-site by "Medical services (hospitalization)" and "Medical services (non-hospitalization)" are very small, amounting to only 2.50 $MtCO_2e$ and 2.56 $MtCO_2e$, respectively, these two categories still account for over six times their direct emissions. This means there are substantial opportunities for emissions reduction in medical service supply chains.

Furthermore, the carbon footprint of the sector "Medical services (pharmacy dispensing)", an inseparable part of medical care, is 8.18 $MtCO_2e$, which is 13.1% of the total carbon footprint. As the direct emissions of this sector are only 0.236 $MtCO_2e$, the emissions generated through the associated dispensing supply chains are about 35 times higher, indicating that reducing expenditure on the dispensing of pharmaceuticals has the potential to cut GHG emissions substantially.

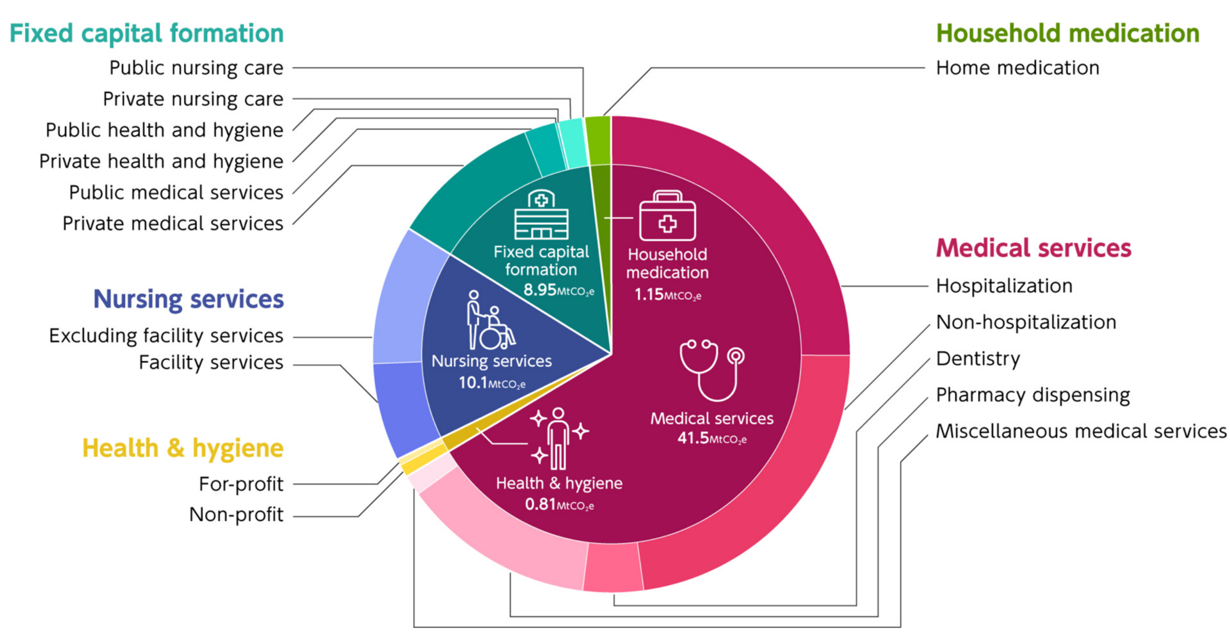

Fig. 1. Carbon footprint of the five general and 16 fine-scale health care service segments in Japan in 2011.

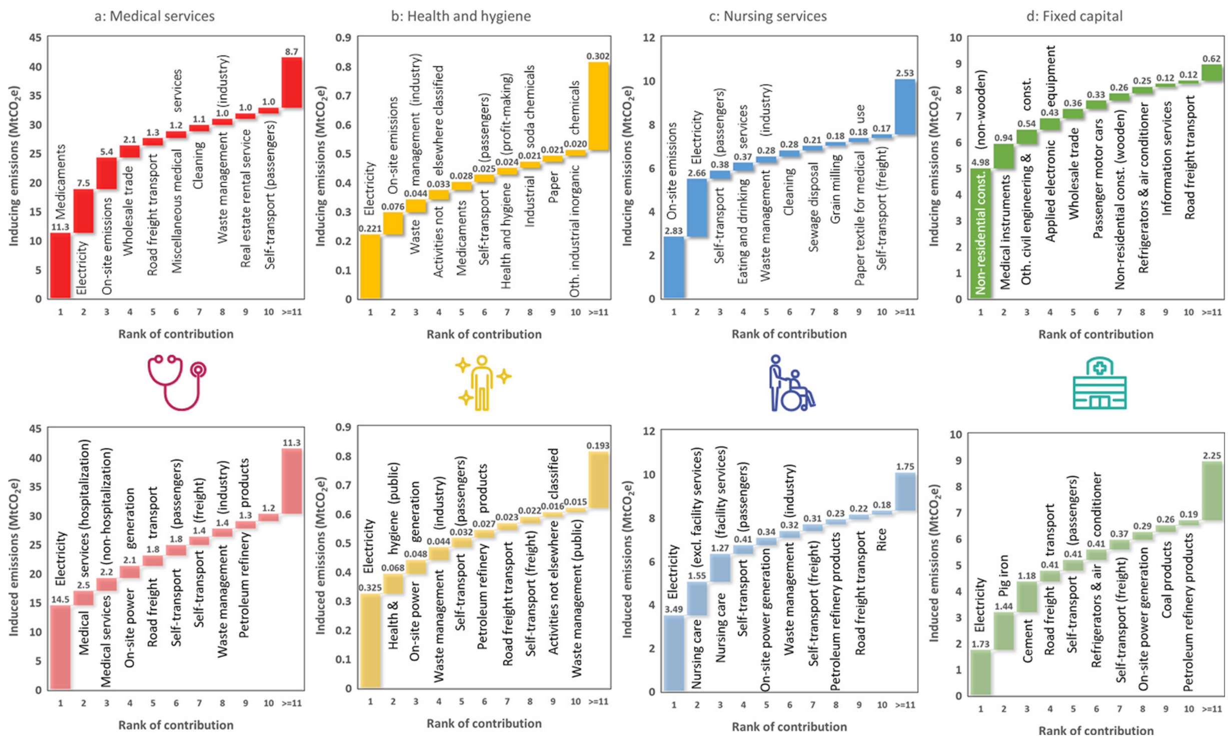

Fig. 2. Top ten purchased commodities in health care services including their fixed capital in Japan in 2011 inducing the highest GHG emissions (upper charts), and top ten sectors with the highest on-site GHG emissions within health care service supply chains (lower charts); a: Medical services, b: Health and hygiene, c: Nursing services, d: Fixed capital formation.

The carbon footprint of “Home medication” is 1.15 $MtCO_2e$.

Another notable finding is that the emissions arising from the categories “Nursing care (facility services)” and “Nursing care (excluding facility services)” continue to increase as demand for these services grows in response to the aging of the Japanese population. The two categories account for a substantial 4.15 and 5.92 $MtCO_2e$ of emissions, respectively, together approximately 16% of total health care-induced emissions. At 1.28 and 1.55 $MtCO_2e$, respectively, direct emissions from the nursing care field are relatively high, due in large part to consumption of fuels such as kerosene, LPG, fuel oil and city gas for heating and cooking.

The dominant source of emissions induced by the fixed capital formation segment is the category “Private fixed capital formation for medical services”, which accounts for 6.39 $MtCO_2e$, while “Private fixed capital formation for nursing care” also accounts for 1.01 $MtCO_2e$ of emissions — a non-negligible figure for emissions arising mainly from construction work related to nursing care.

3.2. Key drivers and emitters of carbon within health care supply chains

The respective upper charts in Fig. 2a–d show, for each of four categories (a: Medical services, b: Health and hygiene, c: Nursing services, and d: Fixed capital formation). the top 10 purchased commodities contributing to the carbon footprints, including on-site emissions originating in purchased fuels. These four categories comprise 15 of the 16 fine-scale health care categories; the correspondences between them are given in Table 1. The respective lower charts in these figures represent the top 10 sectors directly emitting significant GHG emissions throughout the supply chains of the category concerned.

3.2.1. Medical services

As the upper chart of Fig. 2a shows, in the category “Medical services” the biggest contributor to GHG emissions was “Pharmaceuticals” (hospital and home), contributing 11.3 $MtCO_2e$, or 27% of the aggregate carbon footprint of this category. The cradle-to-gate GHG emissions per kg of pharmaceuticals and fine and specialty chemicals are much higher than those of general commodity chemicals, largely because of multiple, low-yield synthesis steps (Parvatker et al., 2019). Beyond the gate, packaging of pharmaceuticals and their transportation to hospitals cause additional emissions, furthermore. These factors result in a footprint exceeding that of the second largest contributor, hospital electricity consumption (7.54 $MtCO_2e$). The importance of reducing pharmaceutical prescriptions and the amount of unused medicines has been understood as a potential means of mitigating rising health care spending (Law et al., 2015; Toh and Chew, 2017). Our study finds that such measures also have considerable potential for cutting GHG emissions, comparable to reducing power consumption in hospitals.

The fourth biggest contributor is “Wholesale trade”, but this is peculiar to Japan, where hospitals have long tended to procure a wide variety of the products they need through trading companies. Total emissions from the business activities of trading companies contribute approximately 5% of the total carbon footprint of “Medical services”. Consequently, one way to reduce this footprint may be to request trading companies to control and reduce their GHG emissions, and/or for hospitals to deal only with trading companies that are already actively striving to cut emissions. Outsourced “Cleaning” services and “Waste management services (industry)” were the seventh and eighth largest contributors to emissions, contributing 2.7% (1.12 $MtCO_2e$) and 2.4% (1.01 $MtCO_2e$), respectively. These figures reflect the fact that the drying of linen and the processing of medical waste by incineration both require large amounts of energy in the form of heavy oil and city gas.

The lower chart of Fig. 2a indicates that direct emissions from the electricity sector were 14.5 $MtCO_2e$, accounting for 35% of the total carbon footprint of the category “Medical services”. Thus, focusing efforts on reducing the GHG emissions associated with power generation, including greater use of renewable sources, will be indispensable for reducing the carbon footprint of “Medical services”. The fifth biggest contributor, “Road freight transport”, the sixth, “Self-transport

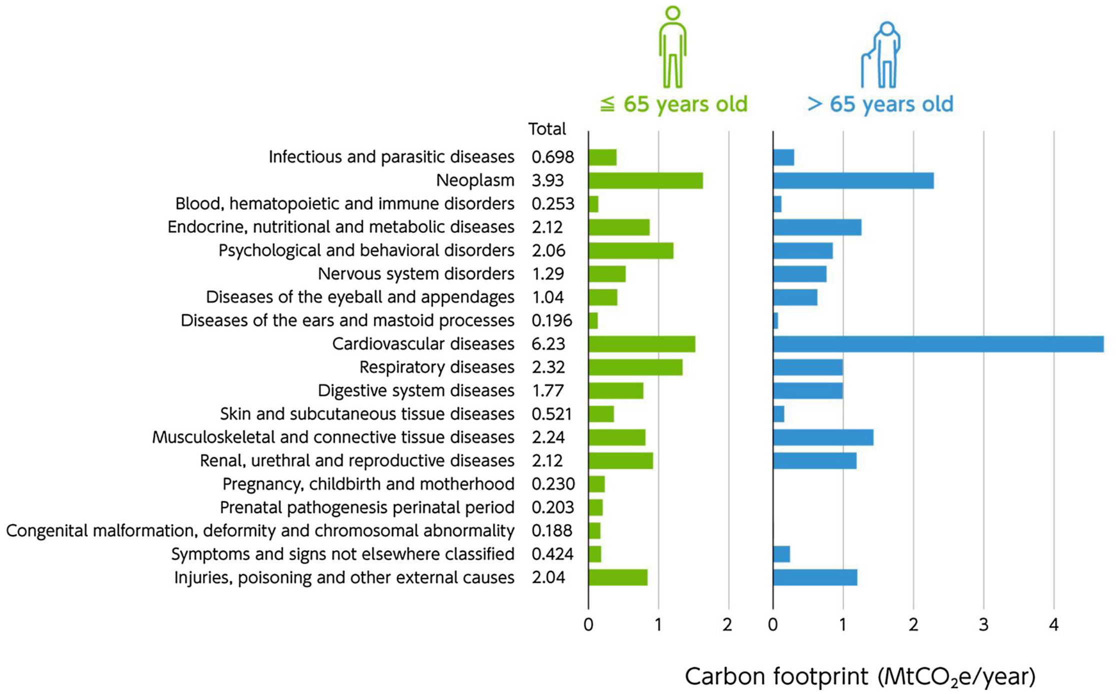

Fig. 3. Carbon footprint of Japanese medical services in 2011 by type of injury/disease and age class (≤65 or > 65 years old).

(passengers)" and the seventh, "Self-transport (freight)", together accounted for total emissions of 5.06 $MtCO_2e$. Technological innovations in the transportation system through introduction of electric and plug-in hybrid vehicles are expected to lead to large emission cuts. However, since such reductions depend heavily on the fuel used to generate the power supplied to the vehicle, in conjunction with this measure it is necessary to also pursue low-carbon power generation. After transportation, another significant contributor is the "Waste management services (industry)." Thus, even in relation to medical waste treatment, people involved in medical services have a role to play in promoting technological improvements from a low-carbon perspective.

3.2.2. Health and hygiene

The upper chart of Fig. 2b shows the main contributors to the carbon footprint of the category "Health and hygiene". Electricity consumption (0.022 $MtCO_2e$) and on-site emissions due to gas consumption (0.076 $MtCO_2e$) account for 27% and 9.4% of the footprint, respectively. "Home medication" is also a significant driver, contributing 3.4% of the footprint.

The carbon footprint of "Health and hygiene" shows similarities to that of "Medical services". In both cases a substantial proportion derives from electric power generation: 40% and 35%, respectively (see the lower chart of Fig. 2b), while at the same time the top 10 contributors include the three transportation-related sectors, which means switching to low-carbon vehicles would be beneficial for emissions reduction in both cases.

3.2.3. Nursing services

The footprint of the "Nursing services" category is similar to that of "Health and hygiene", indicating that the biggest opportunity for emissions reduction lies in on-site fuel and electricity conservation at nursing care facilities (see upper chart of Fig. 2c). The third and tenth biggest emission sources are "Self-transport (passengers)" and "Self-transport (freight)," which together contribute a total of 5.5% of emissions. It is therefore important to continue increasing the transportation efficiency of people and purchased goods, and also to reduce demand for such transportation.

In terms of the major contributors to supply chain emissions (see lower chart of Fig. 2c), "Nursing services" shows approximately the same pattern as "Health and hygiene". It is only in "Nursing services" that "Rice" features in the top 10, however, indicating that generation of CH_4 and N_2O from high global-warming-potential paddy fields is a significant contributor to emissions. This is associated with the provision of meals with rice as a staple at Japanese nursing facilities.

3.2.4. Fixed capital formation

In the category "Fixed capital formation," construction of facilities accounted for 56% of all GHG emissions, with purchase of medical instruments (0.939 $MtCO_2e$), electronic equipment (0.433 $MtCO_2e$) and refrigerators and air-conditioning (0.254 $MtCO_2e$) together contributing another 17.6% (see upper chart of Fig. 2d). One strategy to reduce these emissions is to adopt circular economy principles, a concept that is currently receiving much attention in Europe. Such an approach would encourage repair, equipment sharing, reuse of component parts, and materials recycling (Kane et al., 2018) in relation to medical equipment (without compromising medical care).

The lower chart of Fig. 2d shows that electricity generation is the main contributor to emissions — as it is in the other fields — but here this contribution is relatively minor (19%), while emissions from the production of pig iron and cement for the construction of facilities were similar, at approximately 16% and 13%, respectively. Cement accounts for a large proportion of GHG emissions, not only through fossil fuel consumption, but also through use of limestone as a raw material.

3.3. Breakdown by type of injury and disease

Fig. 3 shows the carbon footprints (total of 29.8 $MtCO_2e$) arising from expenditure in the two categories "Medical services (hospitalization)" and "Medical services (non-hospitalization)", broken down into 19 different medical conditions and also by age (under 65 and 65 and older). As shown in Table 1, the carbon footprint per unit expenditure for "Medical services (hospitalization)" and "Medical services (non-hospitalization)" accounted for 0.989 and 0.958 tCO_2e/MJPY (million JPY), respectively. Since these figures differ by only about 3%, it is clear that the carbon footprints of medical conditions associated with high medical care expenditure are large, irrespective of whether there is

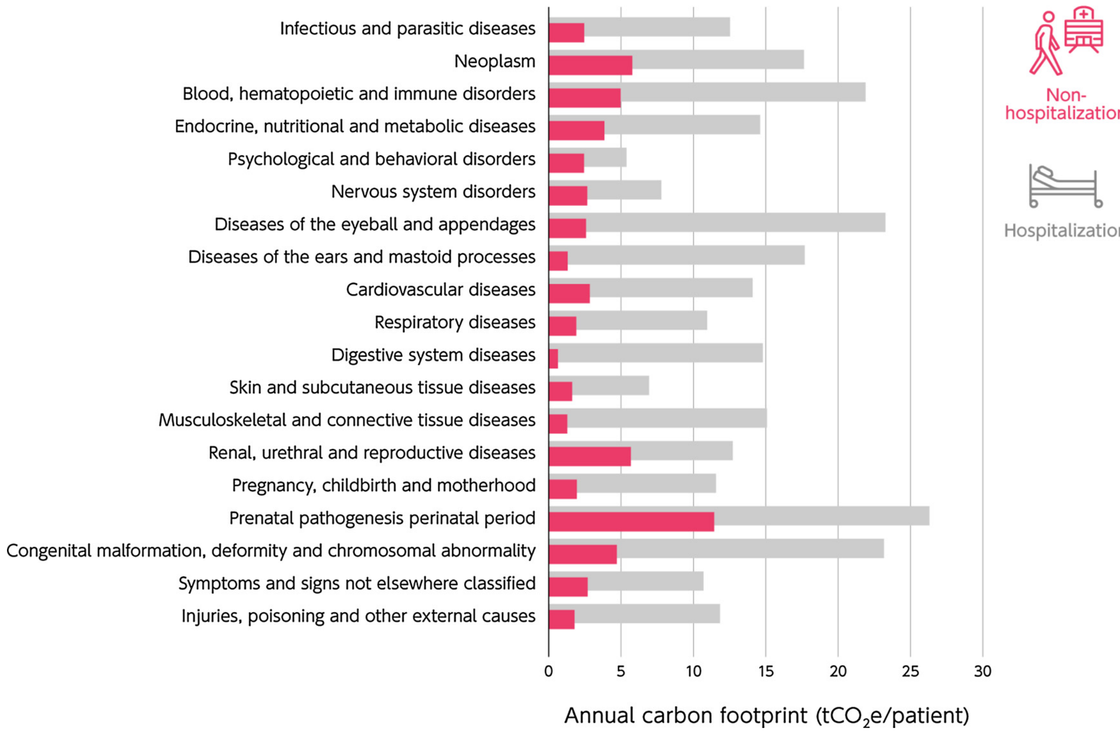

Fig. 4. Carbon footprint per patient by type of injury/disease and form of medical access (hospitalization or non-hospitalization) in Japan in 2011.

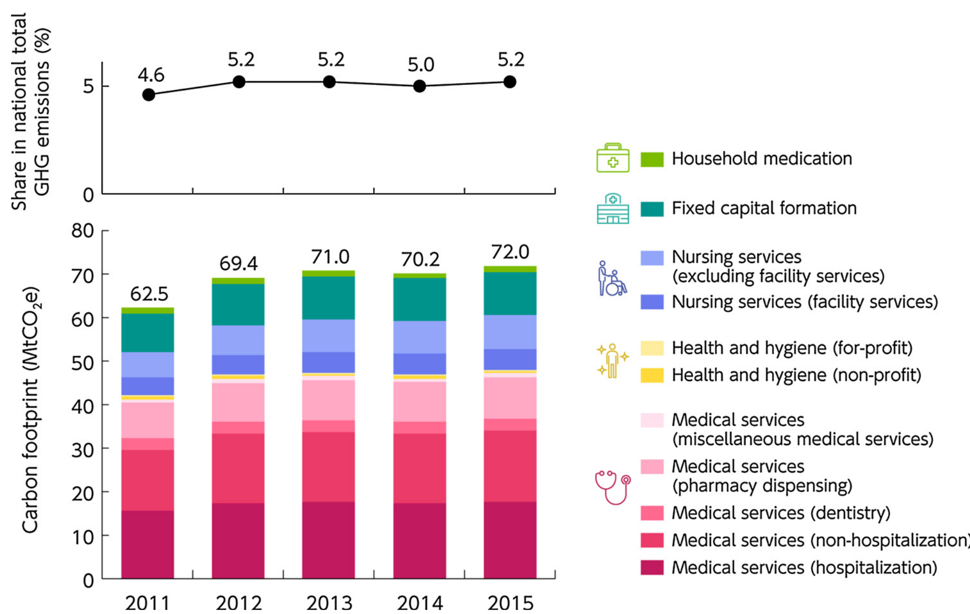

Fig. 5. Percentage share of Japanese health care services in total domestic GHG emissions, 2011–2015, and breakdown of carbon footprint by service category.

hospitalization (inpatient care) or not (outpatient care).

The medical conditions with the biggest carbon footprints are "Cardiovascular diseases" (6.23 $MtCO_2e$), "Neoplasm" (3.93 $MtCO_2e$), "Respiratory diseases" (2.32 $MtCO_2e$), "Musculoskeletal and connective tissue diseases" (2.24 $MtCO_2e$), and "Endocrine, nutritional and metabolic diseases" (2.12 $MtCO_2e$), which together accounted for 56% of the total carbon footprint of medical services. In terms of age, patients aged 65 and older accounted for 58% of the total carbon footprint, confirming that the contribution of elderly people to emissions is high. Most notably, 76% of emissions from "Respiratory disease", 64% of emissions from "Musculoskeletal and connective tissue diseases", and 59% of emissions from "Endocrine, nutritional and metabolic diseases" were attributed to patients aged 65 or older. Note that, as described in the Methods and data section, these emissions were merely allocated proportionally according to relative expenditure on the condition in question, based on the total carbon footprints associated with hospitalization and non-hospitalization. This is therefore solely an artefact of expenditures on cardiovascular disease being higher than those on respiratory diseases, for example.

Fig. 4 reports the carbon footprint per patient for each disease. Compared with the data in Figs. 3 and 4 shows a discernible difference between inpatient and outpatient-related emissions. Overall, GHG emissions from inpatient care amounted to 12 tCO_2e per patient per year, while emissions from outpatient care were 2.1 tCO_2e per patient per year. This means emissions are 5.4 times higher when a patient is hospitalized. This difference between inpatient and outpatient care is most noticeable in the case of "Digestive disease", for which the number of outpatients is highest: 1.3 million patients per year. While emissions associated with inpatients were 14 tCO_2e per patient per year in this case, emissions associated with outpatients were 23 times lower, amounting to just 0.63 tCO_2e per patient per year.

The next biggest difference was seen with "Musculoskeletal and connective tissue diseases", for which a large number of patients (1.0 million) receive care each year. Emissions in this case were 15 tCO_2e per patient per year for inpatients, compared with 1.3 tCO_2e per patient per year for outpatients: a 12-fold difference. These findings suggest that ways to prevent the deterioration of outpatient symptoms, and thus prevent the need for these patients to become inpatients, would be helpful in reducing the carbon footprint of health care.

3.4. Change from 2011 to 2015

Fig. 5 depicts the change in the aggregate carbon footprint of Japanese health care demand from 2011 to 2015 and the change in its percentage share in total Japanese GHG emissions. As demand for health care has steadily increased, the associated carbon footprint has also risen, reaching 72.0 $MtCO_2e$ in 2015 — an increase of 15.3% over this five-year period. Although the main cause of this increase was the growth in medical care and pharmacy dispensing of medical services, the increase in emissions from nursing services suggests that the country's aging population has also had an impact. The carbon footprint per unit demand for health care has slightly increased from 1.06 (tCO_2eq/m-JPY) in 2011 to 1.09 in 2015. The contribution of health care to total domestic emissions is between 4.6% and 5.2%, with a slight upward trend.

Pichler et al. (2019) estimate the global CO_2 emissions by Japanese health care at 114.9 $MtCO_2$ in 2014, which corresponds to 7.6% of the global CO_2 emissions from total Japanese consumption. As about 5.4 of 7.6% account for domestic emissions, we estimate them at 81.6 ($= 114.9 \times 5.4/7.6$) $MtCO_2$. On the other hand, assuming 95% of 70.2 $MtCO_2eq$ in 2014 calculated in this study is CO_2 as same as the percentage in 2011, the domestic emissions are estimated at 66.7 $MtCO_2$. As mentioned in Section 1 for the case of Australia, there are variations in footprint results for Japan, due to the use of different data-sets for undertaking the assessment.

4. Discussion

The greenhouse gas emissions associated with health care in Japan were 62.5 $MtCO_2e$ in 2011 and 72.0 $MtCO_2e$ in 2015, accounting for 4.6% and 5.2% of total domestic GHG emissions, respectively. By way of comparison, if we consider that direct GHG emissions from private cars amounted to 68.5 $MtCO_2e$ in 2011, then it is clear that reducing the emissions associated with health care, which correspond to about 91% of private car emissions, has considerable potential to contribute to climate change mitigation. Since the direct GHG emissions from the health care sector in 2011 were only 8.54 $MtCO_2e$, reducing emissions through the supply chain (in addition to reducing on-site fuel consumption) has the potential to be very effective.

There are two potentially effective approaches for reducing supply chain emissions: reducing demand for the goods and services inducing the emissions (demand side) and promoting technological improvements to supply chain activities that generate emissions directly (supply side). Identified as major drivers and emitters in 2011 were the purchase of pharmaceuticals and aggregate electricity demand by the health care system, accounting for emissions of 11.3 and 10.4 $MtCO_2e$ via the supply chain, respectively, while power generation and on-site fuel consumption had emissions of 20.0 and 8.53 $MtCO_2e$, respectively, within the overall health care supply chain.

The demand side approach would be particularly effective in reducing the consumption of pharmaceuticals and electricity. Efforts are already underway to avoid the generation of unused medicines that have to be disposed of after reaching their expiration date, and this is a substantially effective approach for reducing GHG emissions in the health care sector. Reducing the amount of unused medicines prescribed to patients in Japan has been estimated to save approximately 650 billion yen annually (Masuyama, 2015). A simple calculation using the unit carbon footprint of medications (1.19 tCO_2e/mJPY) in Table 1 means such a reduction could potentially reduce GHG emissions by an estimated 1.24 $MtCO_2e$, slightly more than the footprint of home medication (1.15 $MtCO_2e$).

With respect to on-site energy saving measures, expanding the use of renewable power generation and reducing fuel consumption for transportation could greatly impact health care emissions. It is also important that health care professionals and organizations make demands for these kinds of technological improvements and that they actively engage in providing financial support for the development and introduction of new technologies. In the context of ESG (Environmental, Social and Governance) investment (United Nations, 2019), such efforts to reduce the carbon footprint of medical sectors should also be evaluated by financial sectors, such as the banks financing them.

In addition to reducing emissions by health care service providers, as described above, there is scope for reducing the medical care needs of users. In 2011, 29.5 million people or 23.0% of Japan's total population was aged 65 or older, but this figure increased to 35.2 million people or 27.8% in 2018 and it continues to rise, as Japan becomes a "super-aging society". By 2030 the population of that age is forecast to be 37.2 million people, reaching 38.4 million people in 2050 (Cabinet Office of Japan, 2019). Importantly, approximately 58% (17.2 $MtCO_2e$) of the emissions from "Medical services (hospitalization and non-hospitalization)" were associated with patients aged 65 or older in 2011. If we briefly assume these emissions will grow proportionally to the 65 or older population, they will rise to 21.7 and 22.4 $MtCO_2e$ in 2030 and 2050, respectively, corresponding to increases of 4.5 and 5.2 $MtCO_2e$ relative to 2011. Also, in 2011 emissions linked to nursing services amounted to 11.6 $MtCO_2e$, including fixed capital, but with the continued aging of the population, construction of health care facilities and long-term care facilities for the elderly is growing, and this trend is likely to continue in the future. With a view to achieving the terms of the Paris Agreement in 2030, the Japanese health care sector needs to avoid these potential emission increases.

We have confirmed that one effective way to reduce the emissions associated with medical services is to devote efforts to the prevention of both disease and hospitalization, since the carbon footprints per patient for outpatients and inpatients can differ by a factor of 2–20. In fiscal 2011, 44.7% of the population underwent "specific health checkups" (Japanese Ministry of Health Labour and Welfare, 2017), but it is recommended that effective preventive measures — not limited to health examinations — should be taken to both promote health and reduce carbon footprints.

Another key way to reduce emissions is to promote forms of healthier living that at the same time reduce carbon emissions. This would be a welcome "by-product" of the health imperative, because ordinary people generally care more about their health than about their carbon footprint. For example, there is considerable evidence that adopting a diet restricting the intake of animal-based foods or excessive calories (Behrens et al., 2017; Scarborough et al., 2014; Tukker et al., 2011) or increasing physical activity by walking or cycling instead of driving a car (Lindsay et al., 2011; Woodcock et al., 2009) can improve health. A cross-sectional survey in Japan (Shimoda et al., 2019) discovered a significant association between health consciousness and pro-environmental behavior such as recycling. Hence, by providing further options that both promote health and reduce direct emissions in this way, and by inducing indirect emissions reduction through decreasing demand for health care via improved disease prevention, a practical methodology for "planetary health" that simultaneously improves both human and environmental health would realistically permeate society.

Before elaborating such initiatives in detail, it will be important to undertake a bottom-up inventory of items associated with high GHG emissions, such as electricity consumption, medical equipment, pharmaceuticals, linen services, etc. required for testing or treatment of specific medical conditions.

In this study we focused on domestic Japanese emissions, but many items of medical equipment and pharmaceuticals are imported. In this context we would therefore note that the medical services consumed domestically induce foreign emissions corresponding to about half the associated domestic emissions (Nansai et al., 2009, 2012a; Shigetomi et al., 2014). To reduce the carbon footprint of Japanese health care it is therefore also necessary to take into account the emissions generated outside the country through global supply chains (Pichler et al., 2019). More broadly, it is necessary to look holistically at the worldwide "planetary health" impacts of healthcare, not only in terms of climate change, but also with respect to impacts on water, air, soil and biodiversity in the context of planetary boundaries. It is thus important to foster an environment in which more people understand the connections between their own health and that of the planet, so they can take good care of both in a balanced way. This understanding would further achievement of Sustainable Development Goals 12 (Responsible Consumption and Production) and 13 (Climate Action), while at the same time promoting SDG 3 (Good Health and Well-Being).

Declaration of Competing Interest

None of the authors have any commercial or financial involvement in connection with this study that represent or appear to represent any conflicts of interest.

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