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Japanese carbon emissions patterns shifted following the 2008 financial crisis and the 2011 Tohoku earthquake

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Unexpected events such as economic crises and natural disasters can have profound implications for energy systems and climate change mitigation efforts at different levels. Here we explore the national and regional carbon emission patterns (and their drivers) for the main economic sectors in Japan between 2007 and 2015, a period shaped by the 2008 financial crisis and the 2011 Tohoku Earthquake. Following the 2011 earthquake the previously decreasing regional emissions patterns started increasing in practically all regions except Hokkaido. This was mainly due to growing coal use particularly in the Kyushu, Chugoku and Kansai regions. Furthermore, most regions experienced shifts in the dominance of different drivers of emissions over time, with a stronger initial impact from economic effects after the 2008 financial crisis, followed by energy structure after the 2011 earthquake, and then by economic effects and energy intensity. These results offer a more nuanced understanding of how individual events can affect emissions at different periods and levels (national vs. regional) to inform the design of climate change mitigation strategies.

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The accelerated global economic growth of the past decades has raised concerns about the sustainability of the national energy systems driving this growth, as well as about their environmental impacts[1]. National energy systems have become pivotal elements of the ever-expanding national and international environmental policy landscape, including the 2015 Paris Agreement[2]. Energy mixes are critical components of national energy systems, and are thus central in the ongoing efforts to meet such environmental targets[3]. Long-term economic change and coordinated policy action can shape national energy mixes and their associated greenhouse gas (GHG) emissions, as observed through the major reduction of GHG emission intensity during recent industrial transitions in some countries such as China[4].

However, unanticipated events can have equally important and profound ramifications for energy systems and mixes, and thus on national GHG emissions. For example, both natural and economic events have been found to have rapid and cascading environmental outcomes, even reversing national emission pathways[5]. Such an example was the 2008 global financial crisis that caused a very rapid short-term decline in economic growth worldwide, having major environmental consequences in the process[6]. However, although the 2008 financial crisis affected production/consumption patterns and reduced GHG emissions in many countries in the short-term, in most cases these emissions bounced back rather quickly[5–7].

Japan is one of the countries that experienced major shifts in its energy mix in the last decades, both from coordinated action and unexpected events. As a major industrialized nation, Japan vowed to reach its GHG emissions reduction within 2008 and 2012 by 6% from 1990 level, as part of the Kyoto Protocol[8]. More recently, following the Paris Agreement, Japan, as a major industrialized country has embarked in an ambitious effort to reduce its GHG emissions by 26%, between 2013 and 2030[9]. At the same time, despite being one of the most developed countries and the world's third largest economy, Japan has scarce natural resources in terms of fossil fuels and minerals. As a result, according to the International Energy Agency (IEA), in 2017 Japan ranked 34th out of the 35 member states of the Organization for Economic Co-operation and Development (OECD) in terms of primary energy self-sufficiency ratios[10]. This results in energy policy being closely linked to geopolitical issues[11]. As a result, Japan has actively sought for many decades to ensure its energy security through the diversification of energy sources. Largely due to this reason, nuclear power was historically a major component of the national energy mix (Fig. S1, Supplementary Material), and accounted for roughly as much as coal in power generation[10] (Fig. S2, Supplementary Material). Renewable energy has been a rather minor component of the national energy mix, gaining only recently large attention (post 2011 as discussed below)[10,12,13].

During the first Kyoto Protocol commitment period (2008–2012) Japan experienced two major unanticipated events, namely the 2008 economic crisis and the 2011 Tohoku Earthquake. Both caused abrupt reconfigurations in the Japanese energy system, affecting profoundly the national emissions reduction pathway under the Kyoto Protocol pledges[14]. In retrospect, while both events has profound economic[15] and environmental[16] impacts, the 2011 Tohoku Earthquake had more pronounced effects to the electricity fuel mix (Fig. S2, Supplementary Material). In summary, the major damages to key energy infrastructure caused by the post-earthquake tsunami (most notably to the Fukushima Daiichi nuclear power station), had cascading effects in several energy-related sectors including power and energy generation, petroleum refining, and telecommunications among others[17]. Following the suspension of the Fukushima Daiichi Nuclear Power Plant, Japan faced an abrupt energy supply shortage in the short-term, and a longer-term shift away from nuclear power generation (Fig. S2, Supplementary Material). For example, the capacity factor of the Japanese nuclear power plants dropped from 81.7% (2000) to 3.9% (2012)[18], forcing the country to take substantial measures toward renewable energy promotion, deregulation of electricity market (latter promote a rush a new coal-fired power plants[19]), industrial restructuring and technological innovation[20,21]. These were seen as essential steps toward relieving the immediate pressure posed by increasing fossil fuel demand and imports from countries such as Australia and Russia[16,21,22]. For example, Furthermore, the 2011 earthquake prompted concerns about nuclear safety and nuclear energy policy, casting serious doubts over the future of the Japanese nuclear power generation sector. However, there has been substantial variability between Japanese regions on how the two events affected energy systems, energy use, and associated emissions[23,24].

It is worth emphasizing that around that period Japan pledged its post-2020 mitigation target to the United Nations Framework Convention on Climate Change (UNFCCC). The intended Nationally Determined Contribution (NDC) indicates that Japan is expected to reduce its GHG emissions by 26%, starting in the fiscal year (FY) 2013 and until FY 2030[9]. However, the nuclear accident and its fallout changed Japanese energy policies, making it harder for Japan to achieve its committed emissions reduction targets[25]. For example, in the second year after the earthquake, Japan's national GHG emissions reached 1410 million tonnes of CO_2 equivalent (Mt-CO_2eq), which constitutes a 2.0% increment from 2005 levels[14,26]. However, despite these challenges, Japan became the latest major economy announcing in late 2020 its vision of reaching economy-wide carbon neutrality by 2050[27]. Debates are still ongoing on how to "design" the energy mix in the post-earthquake era without compromising Japan's decarbonization pathways[28–30] (see below).

Under this pivotal timing, there is no single storyline about Japan's future energy use and emissions pathways. Considering the wide range of possible future trajectories and unanticipated natural and economic events (especially following the COVID-19 pandemic), it is important to understand accurately how past events have catalyzed changes in the Japanese energy system (and particularly its energy mix) and affected emission reduction pathways, both nationally and regionally. Although many previous studies have investigated the emission drivers for critical periods[31–37], few have provided sub-national analyses, despite the clear need for a more disaggregated understanding of such phenomena[38,39].

To bridge these knowledge gaps, this study quantifies the national and regional emissions patterns for the major economic sectors such as manufacturing, construction, mining, energy supply, services, and agriculture, forestry, and fisheries (See Table S1, Supplementary Material) in Japan around key events, as well as the factors driving these patterns on the outset of such events. Our analysis focuses on the period between 2007 and 2015, which spans before and after the 2008 financial crisis and the 2011 earthquake, and uses the Logarithmic Mean Divisia Index (LMDI) to decompose the effects of different drivers. Major objectives of this study are to critically explore at the national and regional levels: (1) whether and how emission trends were affected by the 2008 financial crisis and the 2011 earthquake; (2) what has driven the changes in emissions following the events; (3) what are the implications of these events in achieving emissions reduction targets. This disaggregated analysis at the regional level enables the better understanding of the effects of individual events at different periods and levels (national vs. regional), which is lacking from the current literature.

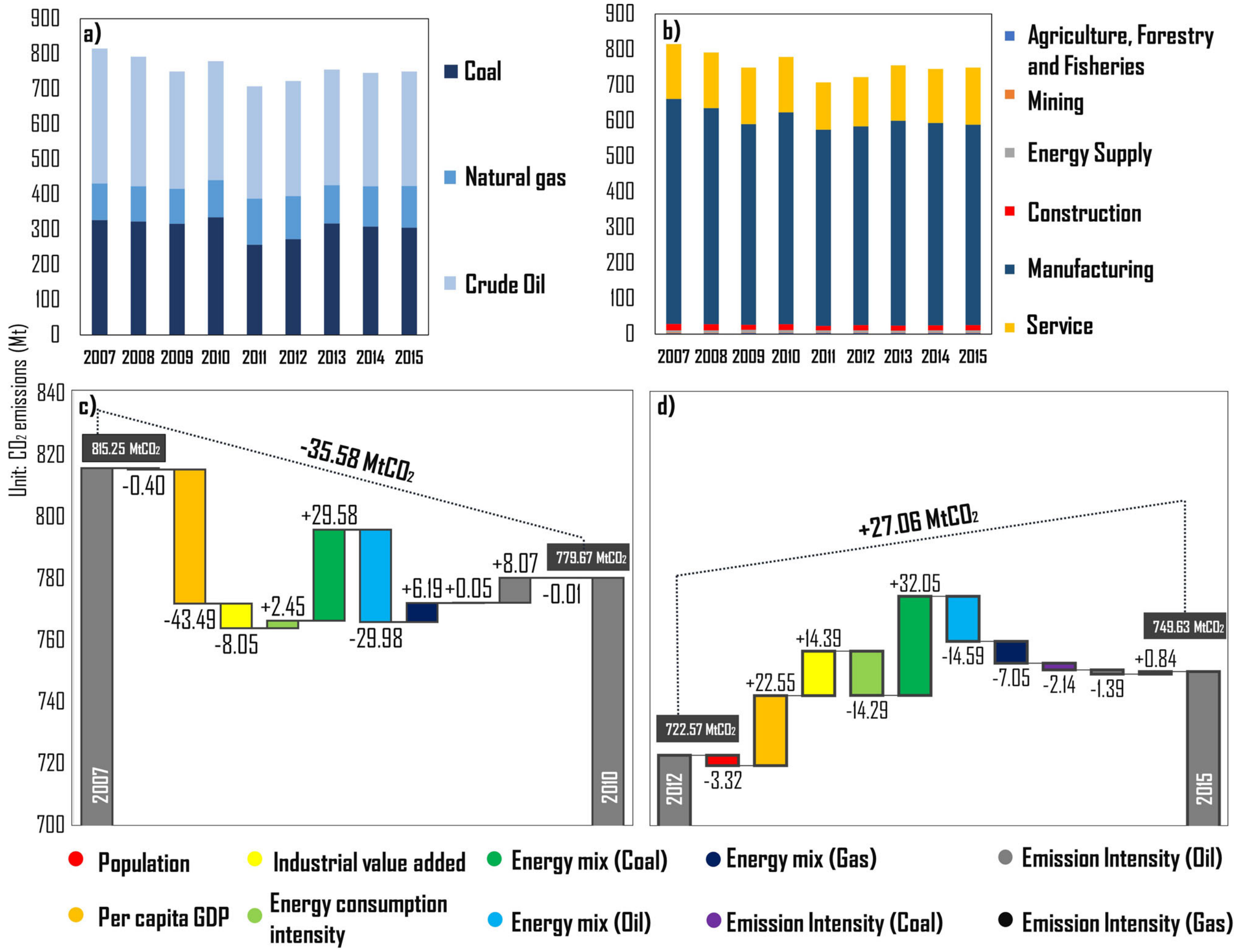

Fig. 1 National emission patterns and drivers. a, b Summarize the total emissions from 2007 to 2015, by fuel type and economic sector respectively (in $MtCO_2$). **c**, **d** Show the effect of each driver on emissions for the periods 2007–2010 and 2012–2015, respectively. Fig. S3 (Supplementary Material) offers a breakdown of emissions by manufacturing sub-sector. The analysis presented in this figure only contains the final energy demand sectors related to the primary, secondary, and tertiary economic sectors (see "Methods").

Results

National emission patterns and drivers. Fig. 1 outlines the emission trends for the main economic sectors and the underlying drivers, spanning the period just before the 2008 financial crisis and after the 2011 earthquake. Emissions overwhelmingly come from the combustion of crude oil and coal from the manufacturing and energy generation sectors, though the fraction of the latter appears to be low due to the re-allocation of electricity to the different economic sectors (see "Methods"). We observe emission decreases in both 2008 and 2011 (i.e., the years of the financial crisis and the earthquake) compared to their previous years (i.e., 2007 and 2010, respectively), which were followed by immediate increases in the years following both events (Fig. 1a, b).

We estimate an emission decline of 35.38 $MtCO_2$ for the period around the economic crisis (2007–2010) (Fig. 1c), and an emission increase of 27.06 $MtCO_2$ in the period after the earthquake (2012–2015) (Fig. 1d), with slight inter-annual variations in both cases. Fig. 1a shows that coal-related emissions increased suddenly following the 2011 earthquake and then stabilized from 2013 onwards. Despite similar increases in natural gas consumption, the associated emissions are far lower compared to the emissions from crude oil and particularly coal. Manufacturing dominates the sectoral emissions (Fig. 1b), with certain sub-sectors such as the chemical and the iron and steel sub-sectors dominating the emissions (Fig. S3, Supplementary Material).

Fig. 1c, d, illustrate the driving forces of these emission fluctuations following the two events. For the period 2007–2010, the estimated decrease of 35.58 $MtCO_2$ is mainly due to the effects of per capita GDP (orange bar) and the share of oil in the energy mix (blue bar). The former shows the strong effect that the economic downturn had on emissions. Conversely, emission trends are completely reversed for the period 2012–2015, with the estimated emissions increase of 27.06 $MtCO_2$ mainly due to the effects of per capita GDP (orange bar), industrial value added (yellow bar) and the share of coal in the energy mix (green bar).

The above strongly suggests that the year 2011 was a turning point in emission patterns for the Japanese economy. In particular, the emission increases following economic crisis were mainly due to the turnaround of the economy, whereas the emission increase in 2011 is mostly explained by changes in the energy mix. However, it is interesting to note that the effects of coal in the fuel mix are evident also in the period before the economic crisis (Fig. 1c, deep green bar), which has some major implications (see "Discussion"). Obviously, both events distorted to an appreciable level the emission pathway of the Japanese economy, but despite the clear evidence of emission fluctuation between years, several of the aspects underpinning these patterns are unclear from the aggregated national view. For example, it is not clear whether these emission patterns/changes are uniform between regions or what is the origin of this extra coal use and emissions. To further investigate such aspects it is important to zoom in and understand better the regional emission patterns and drivers (see next sections).

Regional emission patterns. Before unraveling the regional emission patterns and drivers it is necessary to appreciate better some of the major differences between the study regions. Fig. 2 visualizes the economic structure of the ten regions in terms of contribution of the main economic sectors on the regional GDP between 2007 (inner circle) and 2015 (outer circle). The tertiary sector (orange portion) accounts for the largest share of economic activity in all regions, with the highest contribution being in Kanto (the heart of the Japanese economy where Tokyo is located) and Okinawa (the smallest region in terms of population where tourism is the major industry). The manufacturing sector (deep blue portion) is more prominent in regions such as Chubu, Hokuriku, Chugoku, and Kansai. In Hokkaido, which is by far the less densely populated region, agriculture has the highest contribution to the regional GDP (deep green fraction) compared to other regions, especially the highly urbanized regions of Kanto and Kansai (where Osaka is located). To further appreciate the overall regional economic output, Figs. S4, 5 (Supplementary Material) illustrate the constant regional GDP over time, which is dominated by prefectures from the regions of Kanto, Chubu, and Kansai.

In terms of absolute emission levels, the regions of Kanto, Chugoku, Chubu, and Kansai are consistently the highest emitters considering their central role in the national economy (Figs. S4, 5, Supplementary Material). These regions are the hubs of economic

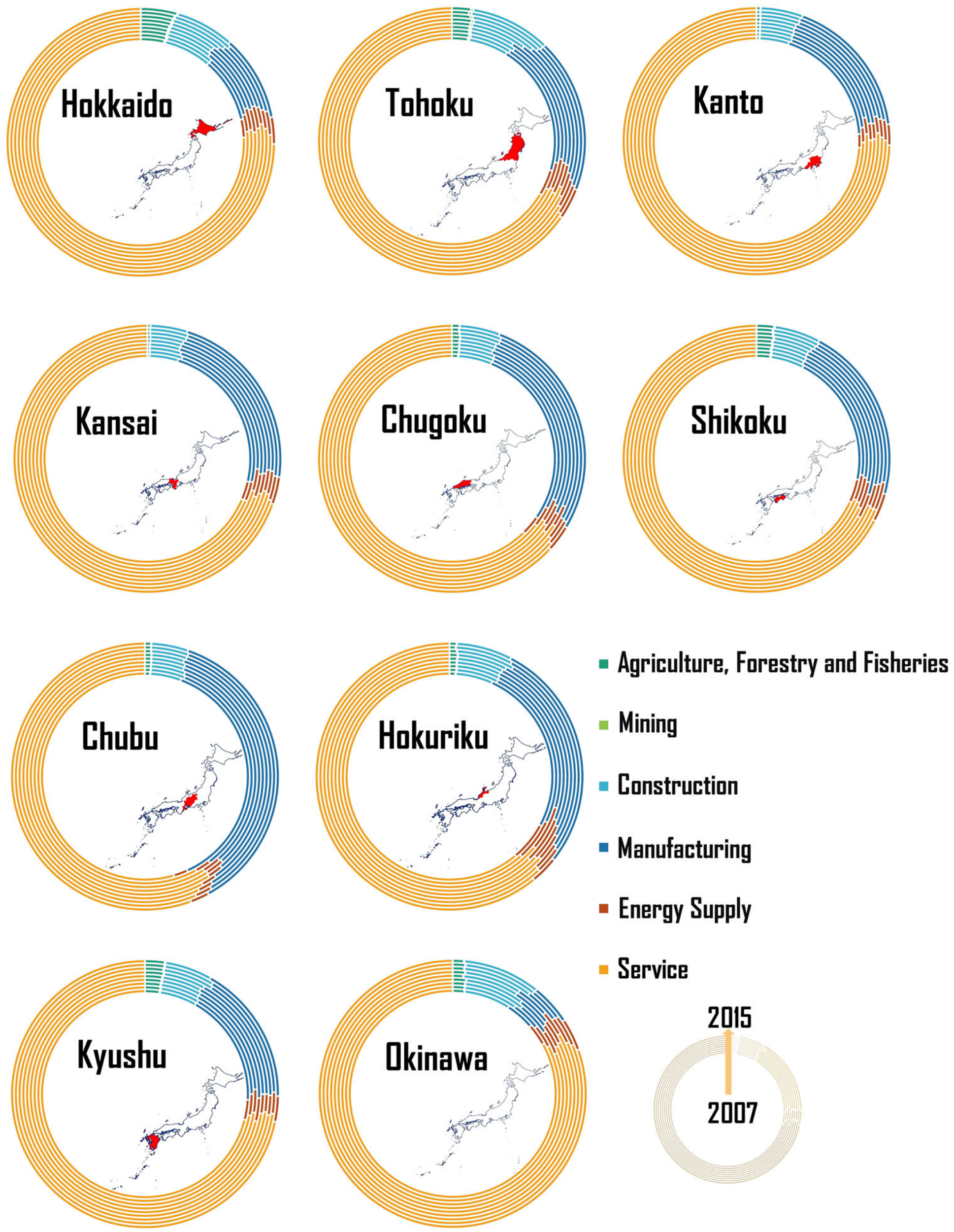

Fig. 2 Contribution of main economic sectors on regional GDP. The six major economic sectors are represented with different colors in each circle. The focus region is indicated inside each circle. The inner-most rings represent the respective regional GDP fraction for the year 2007, and the outer-most rings for the year 2015.

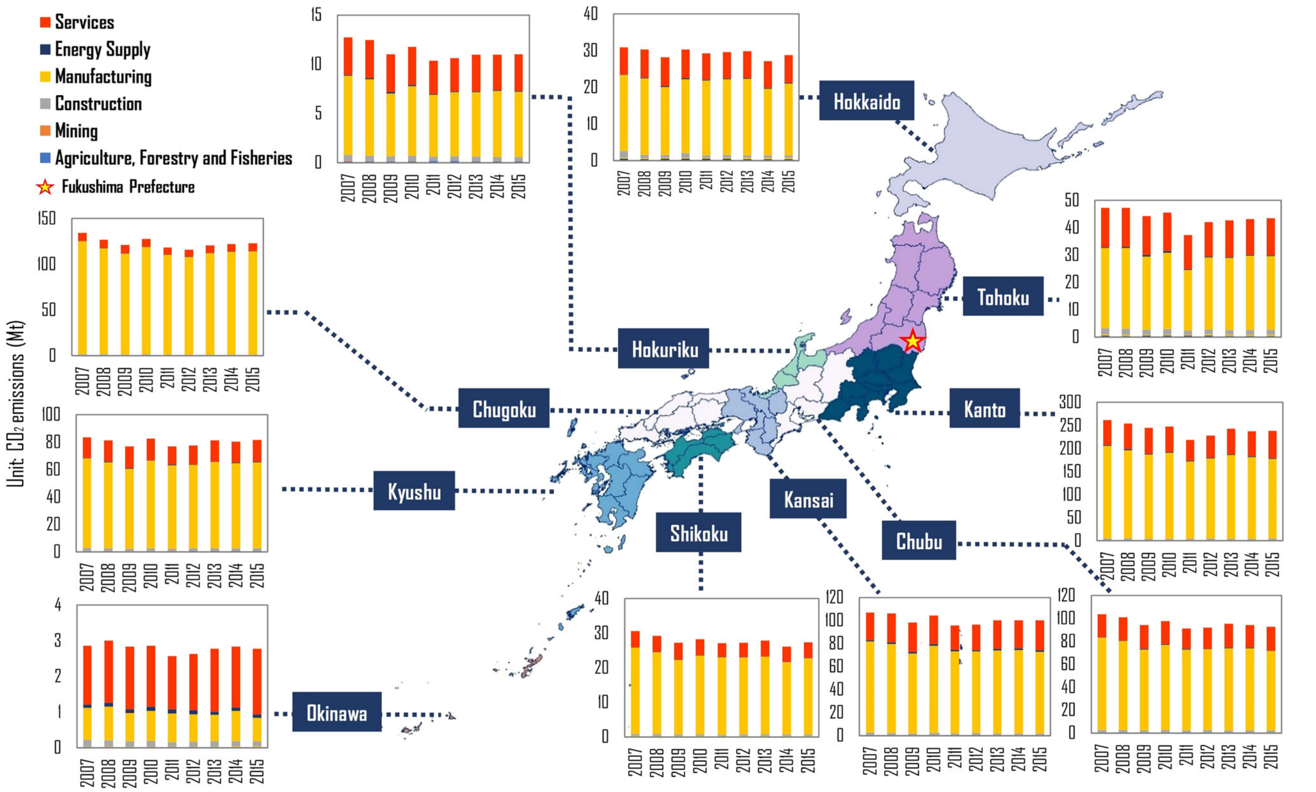

Fig. 3 Regional emissions by economic sector (in MtCO$_2$). Each of the ten regions corresponds to the boundaries of the ten major Electricity Power Suppliers (see "Methods"). The manufacturing sector is the major source of emissions across all Japanese regions, with the exception of Okinawa where the services sector is responsible for the majority of emissions.

activity containing both large concentrations of heavy industry and services in major urban agglomerations such as Tokyo, Yokohama, Osaka, Nagoya, and Hiroshima. Although in most regions the tertiary sector accounts for a greater fraction of the regional GDP (Fig. 2), the manufacturing sector is the greatest source of emissions in absolute terms (Fig. 3). In fact for all regions, with the exception of Okinawa, the manufacturing sector is responsible for most of the emissions. Manufacturing accounts for as much as >90% of overall emissions in some regions such as Chugoku that are characterized by the large concentration of heavy and petrochemical industries.

Overall, sectoral emission patterns do not show much variation in most regions during the study period (Fig. 3). However, the regional emission patterns by economic sector imply that the ratio of manufacturing (shown in Fig. 2) and the overall economic level (shown in Figs. S4, 5, Supplementary Material) might affect substantially the emission patterns (see next section).

Conversely, there is substantial change in emission patterns by fuel type over time (Fig. 4). In some prefectures, there is a very obvious increase in the emissions from coal and oil products after the 2011 Tohoku Earthquake. For example, coal-related emissions increased in regions such as Kyushu, Tohoku, and Kansai, while the highest oil-related emissions have been steadily observed in Kanto. The penetration of natural gas (and associated emissions) has varied substantially among regions, with the highest emissions observed in Hokuriku and the lowest in Hokkaido.

What is important to note is that almost all regions experienced a decline in emissions following the 2008 economic crisis and the 2011 earthquake, though to different extents. However, this variation is lower in regions such as Okinawa and Hokkaido, which are both characterized by low populations, large distance from the main economic centers of Japan, lower concentration of manufacturing, and large distance from the earthquake's epicenter and Fukushima nuclear power plant (at least for Okinawa). Furthermore, similar to the national level analysis from the previous section it is very interesting to note that fuel-specific emissions varied in most regions after the 2011 earthquake but not so much after the 2008 financial crisis. The above suggest that indeed both events had major economic and environmental ramifications across the different regions, but as discussed in the next section this happened through different pathways and had completely different outcomes.

Regional emission drivers. Across most of the study regions there is a consistent pattern of emission decrease prior to the earthquake and emission increase on its aftermath (Figs. 3, 4). However, both the absolute levels and the underlying drivers of these emission changes vary substantially between regions (Fig. 5).

In most of the regions registering the highest overall emissions (Figs. 3, 4) and emission increases such as Kanto (Fig. 5c), Chubu (Fig. 5d), Hokuriku (Fig. 5e), Kansai (Fig. 5f) and Kyushu (Fig. 5i), the most significant driver is the increased use of coal. As mentioned in the previous section, most of these regions are characterized by high concentration of manufacturing, which requires substantial energy input. This finding strongly points to the switch from nuclear energy to coal for electricity generation after the 2011 earthquake outlined in the previous sections.

However, coal use is not always the most significant driver of emission change across regions, as for example in Chugoku (Fig. 5g) and Hokkaido (Fig. 5a). In both these regions GDP structure and energy intensity have had the largest effect on emissions increment (see below). Instead, GDP structure contributes to emission increases in Chugoku (Fig. 5g), and to

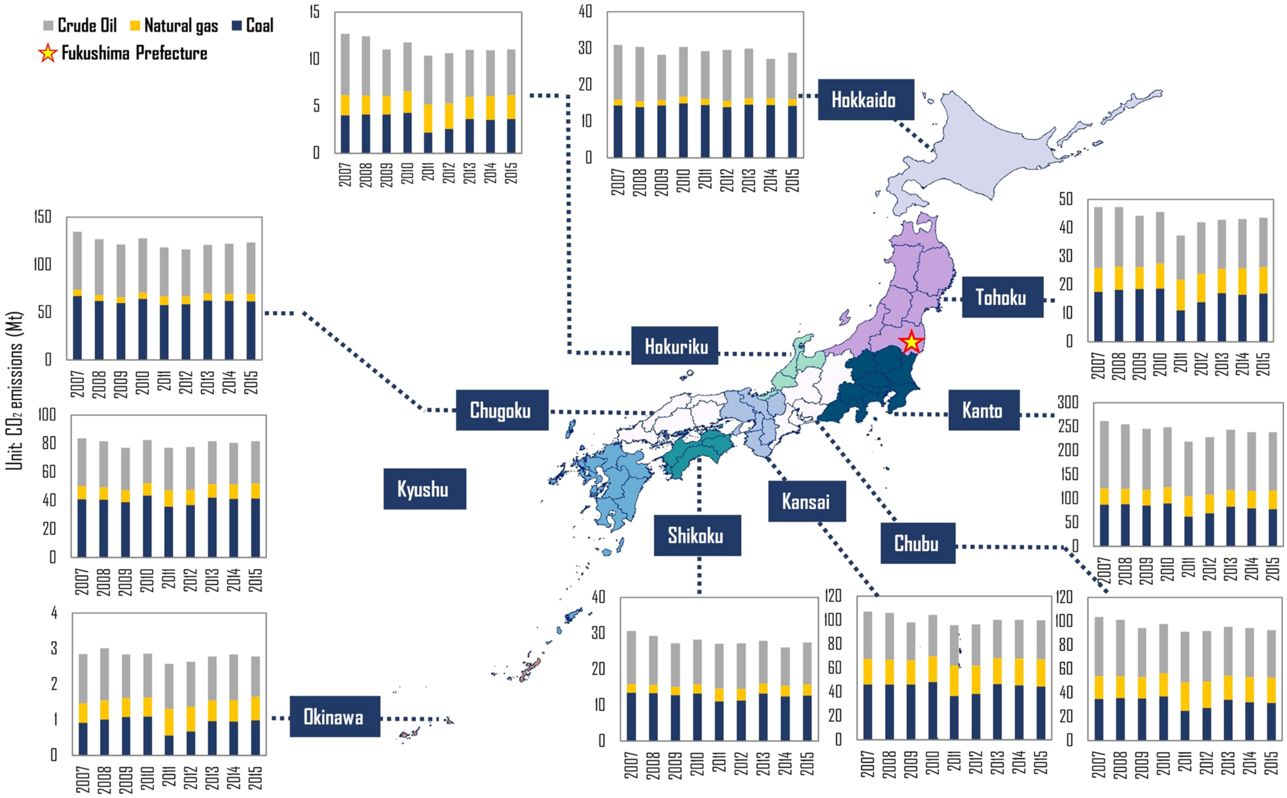

Fig. 4 Regional emissions by fuel type (in $MtCO_2$). Each of the ten regions corresponds to the boundaries of the ten major Electricity Power Suppliers (see "Methods"). Most of the emissions come from coal and crude oil use.

emission decrease in Hokkaido (Fig. 5a), which indicates that economic development and reconstruction may induce short-term emissions increases (Fig. 5). Besides, it is worth noting that energy efficiency (i.e., associated with the energy intensity effect) is consistently the most significant driver of emissions decrease in all regions apart from Chugoku and Shikoku.

To further unravel the effects of different drivers on regional emissions, Fig. 6 aggregates the ten different drivers outlined in Fig. 5, in five overarching categories and presents their comparative effect across regions and years. Despite the large variability between regions, it is possible to discern some basic patterns. Generally, regional emissions are barely affected by drivers related to population and emission structure both before and after the 2011 earthquake. Drivers related to economic effects, have affected emissions in all regions except Shikoku and Okinawa, with their highest influence observed around the economic crisis (see peaks in 2009–2010 period). Drivers related to energy structure have had the greatest effect after the 2011 earthquake (see peaks in 2012–2013), while afterward energy intensity has had a more significant effect (see increasing patterns around 2014–2015).

Fig. S6 (Supplementary Material) offers a different visualization of the relative effect and dominance of the different aggregate drivers. Reflecting the points made above, Fig. S6 (Supplementary Material) shows this change of dominance from economic effects, to energy structure, and then back to economic effects and energy intensity. In more detail, Fig. S6d (Supplementary Material) clearly illustrates the dominant effect of energy structure in driving emission changes in 2012–2013 practically across all regions. Conversely, economic effects play the most significant role in 2009–2010, on the aftermath of the 2008 financial crisis (Fig. S6c, Supplementary Material). The energy intensity effect becomes the most significant driver of regional emissions from 2014 onwards (Fig. S6e, Supplementary Material), partially offsetting the increase in regional emissions (Figs. 3, 4).

Discussion

Synthesis of main findings. Our results suggest that the total emissions of the Japanese economy at the national and regional level fluctuated significantly around the 2008 financial crisis and the 2011 earthquake, though more prominently in the latter case (Figs. 1–3). There are significant emission declines in practically all regions following each event, with the exception of Okinawa after the 2008 financial crisis, and Hokkaido and Okinawa after the 2011 earthquake. Various studies have shown that unanticipated events such as financial crises or natural disasters can affect emission patterns, even disrupting coordinated efforts to reduce GHG emissions or achieve decarbonisation[5,6,40].

At the same time there are strong signs indicating changes in the energy mix, especially after the 2011 earthquake. In particular, there is a very visible shift in the energy mix toward greater fossil fuel use to cope with the energy shortage following the continuous suspension of nuclear power plants (Figs. S1, 2, Supplementary Material). This shift toward greater coal use was the most important driver of emission increases after the 2011 earthquake (Fig. 1), and points to the profound changes that unexpected events such as financial crises or natural disasters can have for energy systems, including energy mixes[5]. However, it is interesting to note that coal use changes also exerted a major influence on emissions even before the earthquake (Fig. 1) (see also next section).

When looking into regional emission patterns, and the factors affecting them, it is safe to say that the different drivers such as population, economy (per capita GDP and economic structure), energy intensity, energy mix (by fuel) and emission intensity (by

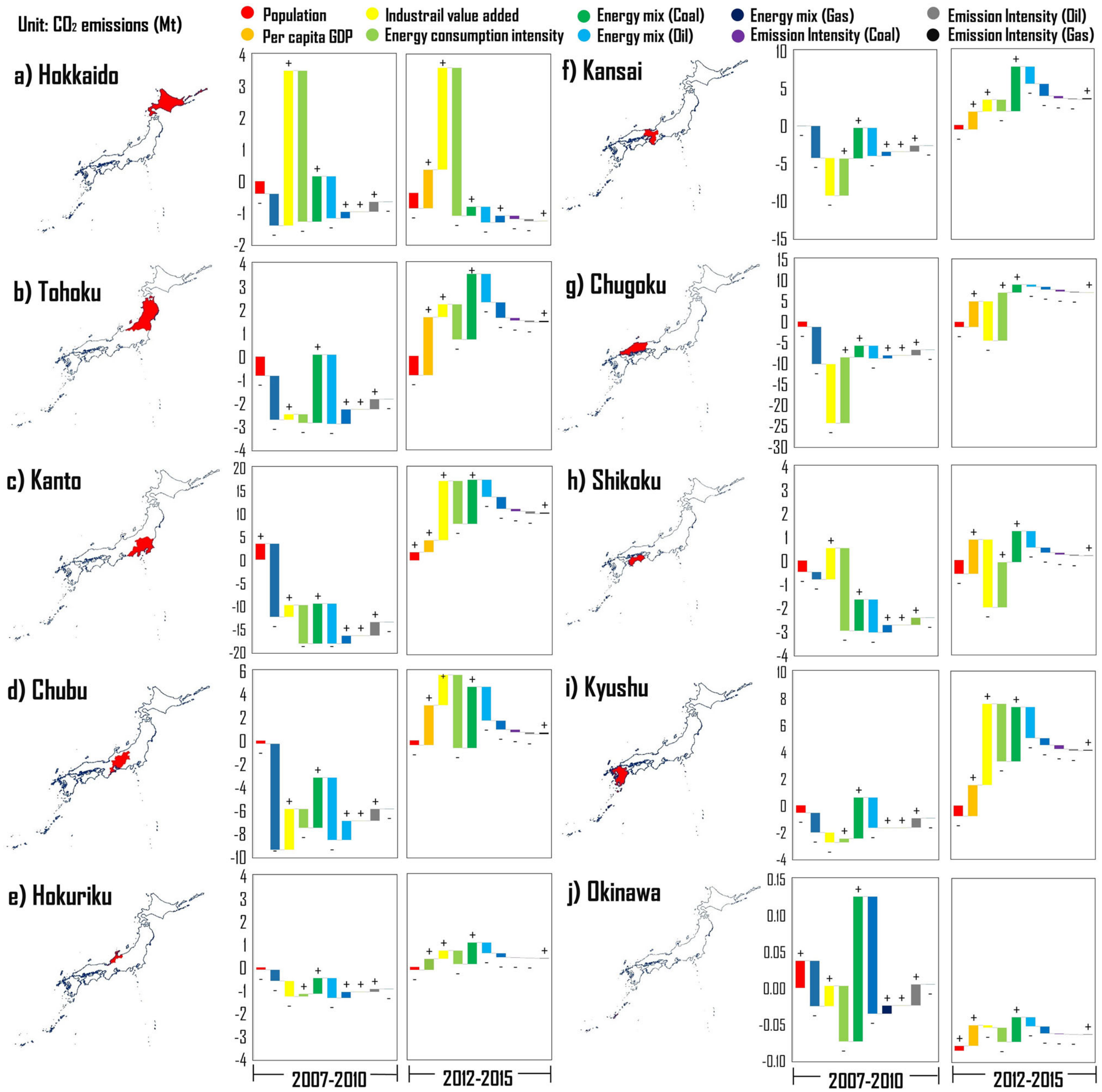

Fig. 5 Drivers of emissions before and after the 2011 Tohoku earthquake. a–j Contain waterfall charts that indicate the effect of different drivers on regional emissions. Each of the ten regions corresponds to the boundaries of the ten major Electricity Power Suppliers (see "Methods"). In each panel, the waterfall charts on the left identify the effects of the different drivers on emissions before the 2011 Tohoku earthquake, and the charts on the right identify the effects after the earthquake. The different colors represent the effects of different drivers. Each bar chart shows overall emissions changes associated for each driver, with positive signs indicating that the respective driver increases emissions and negative signs that it reduces emissions.

fuel) have had differentiated effects over time across regions (Fig. 6; Fig. S6, Supplementary Material).

First, after the 2011 earthquake, the disruption of energy supply due to the suspension of nuclear plants was mitigated at the national and regional level through the expanded use of coal and natural gas (Fig. 1; Fig. S1, Supplementary Material). However, despite increased natural gas use, it was mostly the expansion of coal use that drove up emissions at both the national (Fig. 1) and regional level (Fig. 5). This is especially the case for regions such as Kanto, Kansai, and Kyushu that are major economic centers (see also energy structure effect in Fig. 6).

Second, energy intensity was the main driver consistently contributing to emissions decline, at the national level (Fig. 1) and across most regions (Fig. 5). This effect became much more pronounced toward the end of the study period (see also energy intensity effect in Fig. 6). However, even though most Japanese regions have benefited from energy efficiency improvements, it can still be improved further in some regions such as Hokuriku.

Third, it is important to note both the large regional and temporal variability in the effects of the different drivers. For example, although the 2011 earthquake largely catalyzed in most regions changes in emission sources via the strong energy structure effect, in a few regions other drivers such as economic effects had a more profound impact on emissions patterns (Fig. 5, Fig. S6, Supplementary Material). Similarly, in most cases there were shifts in the dominance of different drivers over time even in

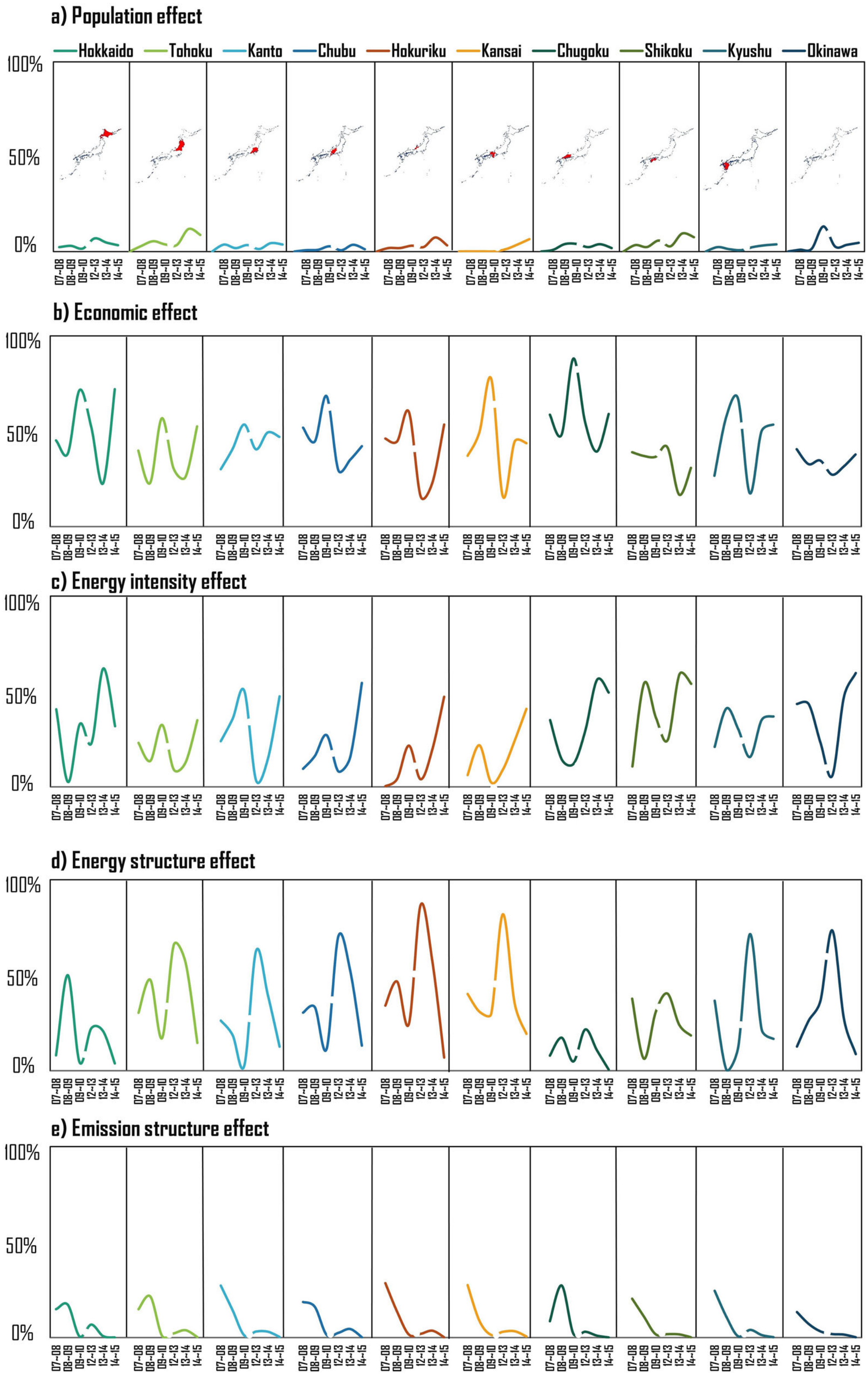

Fig. 6 Comparative effects of aggregate drivers on emissions. The ten individual drivers outlined in Figures 1 and 5 are aggregated in five major categories. **a**–**e** Show the normalized effect of a given aggregate category on regional emissions during the study period, namely population effects (**a**), economic effects (**b**), energy intensity effects (**c**), energy structure effects (**d**) and emission structure effects (**e**). In each panel, the trend lines on the left focus on the period before the earthquake (2007–2010) while the trend lines on the right focus on the period after the earthquake (2012–2015). For each region and year the values for the different effect categories add up to 100%. The higher the score for a single category for a given year, the stronger is its influence on regional emissions.

the same region, as shown through the stronger initial impact of economic effects after the 2008 financial crisis, followed by energy structure after the 2011 earthquake, and then by economic effects and energy intensity (Fig. 5, Fig. S6, Supplementary Material).

However, despite its strength this study has a series of limitations. The first limitation related to the uncertainty over the allocation of electricity emissions. Due to the lack of official data on regional electricity-related emission we resorted to investigating each electric power generation company in order to distinguish both their fuel use and the prefectures/regions they supported. As some prefectures are supported by two major companies, we chose to use the one with the larger coverage area. However, we do not expect this to affect significantly the overall findings, as this assumption affects only seven cities from three prefectures.

Policy implications. Arguably, the 2008 financial crisis and the 2011 Tohoku earthquake brought extraordinarily large shocks to the Japanese economy, affecting significantly the national and most of the regional emission patterns (Figs. 1–5). Arguably, when considering the uniqueness of these events, the actual findings of this study may not be directly applicable to the current efforts to meet the nationally determined contributions (NDCs) and decarbonise the economy (see "Introduction"). However, some of our findings can help indicate priority areas for climate change mitigation strategies, including at the sub-national level. Indeed, the substantial spatial and temporal heterogeneity of emission patterns, and their sensitivity to individual unanticipated events implies the need for spatially- and temporally-differentiated, and adaptive approaches to emission mitigation, As discussed below, this becomes particularly pertinent in light of the increasing importance of emission mitigation efforts at the sub-national level, Japan's vulnerability to natural disasters, and the expected economic downturn following the recent COVID-19 pandemic[41].

Sub-national emission mitigation efforts have a relatively long history in Japan, following the 2005 Act on the Promotion of Global Warming Countermeasures[42]. However, the progress has been rather slow, as more than half of the Japanese prefectures have not set long-term mitigation goals[43] and only Yamanashi city had established a localized zero-carbon target in 2009[44]. However, since 2019, there has been a booming interest in customized sub-national mitigation plans. According to the Ministry of Environment (MOE) and the Local Decarbonization Realization Hearing Conference of Japan Cabinet, ~370 cities have committed to reach zero-emission targets before 2050, accounting for more than 86.8% (about 110 million people) of the national population (update on 17th April. 2021)[44]. However, sub-national emission mitigation efforts and goals still lack clarity in terms of detailed reduction pathways for specific regions and sectors.

The first major policy implication of this study relates to the identification of priority areas for sub-national mitigation plans. Based on our findings, and reflecting ongoing discussions on industrial decarbonization in Japan[45,46], we believe that the manufacturing sector should be one of the main priorities in such emission mitigation efforts. This is particularly important for carbon-intensive industries such as iron, steel chemical and energy, and regions where the industrial sector makes up for a large fraction of emissions such as Kanto, Chugoku, Chubu, Kansai, and Kyushu in order of importance.

A particular priority area within the industrial sector should be coal-related emissions, which account for ~20% of the overall industrial emissions in Kanto, and 30–40% in the other four priority regions. However, as coal-based energy generation generally has much higher emission intensity compared to other fossil fuels, even with the implementation of clean coal technologies (e.g., integrated coal gasification fuel cell combined cycle, IGFC) for high-efficiency gas turbines[47], there would be a need for phasing out coal-based electricity generation, which still has a long way to go. However, industrial decarbonization through phasing out coal might be particularly complicated in regions such as Kanto compared in the four other regions considering the large fraction of natural gas in its energy mix. This implies the possible need for deploying carbon dioxide removal technologies (CDR)[48] in key industrial clusters in regions such as Kanto, rather than optimizing energy mix and reducing energy consumption. Additionally, context-specific measures targeting energy intensity could further offset emissions in most regions, with Chugoku and Shikoku having significant potential to further improve energy intensity.

The second major policy implication relates to the better understanding of the drivers of carbon emissions, including coal use. In more detail, although we find that coal use has driven most regional emissions patterns after the 2011 Tohoku earthquake, this was not completely triggered by the earthquake. There is evidence to suggest that the fraction of coal in some regional energy mixes had already been increasing carbon emissions even before the 2011 earthquake (Fig. 5). Studies have identified this "early" shift to coal-fired power generation and have linked it to efforts toward increasing energy diversification and energy security[19,47]. Indeed studies have suggested that this had affected national GHG emissions and compliance with the Kyoto Protocol commitments[49,50]. This implies that some of the fundamental reasons of the increasing coal share in the energy mix are still geopolitical and economic in nature[51,52]. In this sense the 2011 earthquake possibly accentuated this process, making it harder for Japan to reduce its reliance on coal for power generation.

What our analysis offers beyond these other studies is the relative effect of this shift for national and regional emissions compared to other drivers of emissions. For example, we found that coal use has not driven emissions in all regions after the 2011 Tohoku earthquake such as in Hokkaido and Okinawa (Figs. 5, 6). Conversely, the expanding coal use has driven significantly emissions in regions such as Kyushu, Kansai, and Chubu, while change in industrial structures largely drove emissions in Kansai and Kanto (Figs. 5, 6). In other word, there is disparity in the drivers of emissions (and thus of the effect of coal use expansion) among regions, with emission mixes and trends diverging among regions after the Tohoku earthquake. This further points to the need for more for differentiated and adaptive responses to emission mitigation as suggested above.

We should point here that despite the regional focus of our study and the identification of spatially differentiated emissions drivers, patterns, and priority areas, our study is still rather coarse to directly inform the development of sub-national emission reduction plans. As per the current policies, such plans should focus more on prefectures and clusters with similar emission characteristics, or even to individual cities, rather than the aggregated regions based on electricity company coverage explored in our paper. Thus more fine-grained studies that delve deeper in the particularities of each region at higher resolutions would be needed to inform comprehensive sub-national green growth and development plans[53–55].

Finally, if anything this study has shown that individual events can have strong effects on national and regional emissions. In this sense the COVID-19 pandemic and its expected economic downturn would most likely have an effect on GHG emissions, and thus affect progress to meet NDCs and carbon neutrality goals[56]. However, it is unclear whether this would play out in exactly the same manner as for the 2008 financial crisis and the

2011 Tohoku earthquake. In this sense, future studies should seek to shed light on decomposed emission drivers and provide a compelling assessment on the outcomes of the COVID-19 pandemic on regional emissions. This could allow the Japanese government to identify better feasible climate mitigation strategies. We expect that such findings will be critical to Japanese stakeholders who face the challenging task of deciding the appropriate energy mix in the face of economic, geopolitical, and social imperatives, while keeping in check with its NDCs and carbon neutrality vision.

Limitation. One of the major limitations of this study is the inability to provide a breakdown of emissions by different technologies. For example, different coal technologies do have differences in emission intensity[57–59]. However, there is no readily available and consistent data on plant-specific technologies and fuel consumption in Japan. Thus in this study, we do not conduct a detailed "bottom-up" analysis. Instead we use "top-down" electricity company, as (a) coal consumption in Japan is completely met through imports[60,61], and (b) high-efficiency power generation technology is promoted among electricity companies[62]. As a result there are no obvious differences in emission intensities among companies/regions, with the only difference being Okinawa (0.000696 t-CO_2/kWh) compared to the other nine regions explored in this study (0.000445 t-CO_2/kWh) in the year of 2019[63]. However, since the focus of this study is on the regional level, this does not affect substantially the reported results. Such a "bottom-up" approach would have been necessary if we narrowed our research scope into the city or prefecture scale, and would be necessary to inform in more detail regional emission mitigation plans (refer to "Policy Implications").

Methods

Aggregate regional and sectoral carbon emissions. We estimate aggregate regional carbon emission patterns for the six major economic sectors for the period 2007–2015. For each prefecture, we use data on electricity consumption and the three major fossil fuels (i.e. coal, crude oil, natural gas). And we aggregate the 47 Japanese prefectures in ten regions, which correspond to the boundaries of the ten major Electricity Power Suppliers (Fig. S7, Supplementary Material). The six major economic sectors consist of 23 economic sub-sectors, and are (a) Agriculture, Forestry, and Fisheries, (b) Mining, (c) Construction, (d) Manufacturing, (e) Energy, and (f) Services (Table S1, Supplementary Material).

As the focus of this study is the primary, secondary, and tertiary economic sectors of the Japanese economy, we do not consider direct emissions from the household, transport, and non-energy use sectors (i.e. sectors that emit GHGs without consuming energy such as industrial processes and waste incineration). In particular direct emissions from both passenger and freight transport are excluded from this analysis, as they fall outside the formal definition and scope of the transport and postal industry[64]. This particular economic sub-sector contains activities related to transport and postal services (e.g. warehouse, transport service, postal service), with the relevant emissions included in this study (Table S1, Supplementary Material).

The carbon emissions estimated in this study correspond to the emissions of the three primary fossil fuels used for energy generation, namely coal, crude oil, and natural gas. It is important to note that the regional fossil fuel consumption data does not include data related to electricity. Therefore, we calculate the sectoral emissions in two steps, i.e. non-electricity-related emissions and electricity-related emissions.

First, we calculate the direct non-electricity-related fuel consumption for all economic sectors and regions through Eq. (1):

$$EM_{non-t} = \sum\sum\sum E_{i,j,r,t} \times EF_{j,t} \quad (1)$$

where EM_t indicates the total carbon emission in Japan for year t; $E_{i,j,t,r}$ expresses the carbon emission from economic sector i due to the direct consumption of fuel type j in region r, for the year t; with, $i = 1, 2, 3, \ldots, n(n = 24)$; $j = 1, 2, 3(\text{Coal, Crude Oil, Natural Gas})$; $r = 1, 2, 3, \ldots, n(n = 10)$. $EF_{j,t}$ is the emission coefficient of fuel j for the year t. The details and breakdown of economic sectors is shown in Table S1 (Supplementary Material).

Second, we calculate the electricity-related emissions for all economic sectors and regions through Eq. (2). In order to allocate electricity-related emission into the individual regions within which it is consumed, we first extract the electricity consumption statistics by economic sector for each region. According to location we identify the supporting power plants, and we then use respective energy mix of the power plant to decompose electricity-related emissions into the different types of consumed fossil fuels:

$$EM_{elt-t} = \sum\sum\sum K_{i,r,t} * M_{j,r} \times EF_{j,t} \quad (2)$$

where $K_{i,j,r,t}$ is the electricity consumption (in KWh) by economic sector i in region r for the year t; with, $i = 1, 2, 3, \ldots, n(n = 24)$; $r = 1, 2, 3, \ldots, n(n = 10)$. $M_{j,r}$ is the consumption ratio of fuel types j; $j = 1, 2, 3(\text{Coal, Crude Oil, Natural Gas})$, and $EF_{j,t}$ is the emission coefficient of fuel j for the year t. It is important to note that although the study economic sectors include the Energy sector (which contains electricity, gas and heat supply), the electricity-related emissions are allocated to each of the six study economic sectors based on their electricity consumption, rather than Energy sector whose emissions represent that of the actual energy conversion process.

Therefore, the total emissions for all economic sectors of year t can be estimated through Eq. (3):

$$EM_{total-t} = EM_{elt-t} + EM_{non-t} \quad (3)$$

Decomposition of the drivers of regional emissions. In order to decompose the effects of different drivers on regional emissions we consider different methodological options such as structural decomposition analysis (SDA) and index decomposition analysis (IDA)[65]. The SDA is based on input-output tables and can decompose emissions changes in terms of input-output technique, sectoral GDP, and final demand, among others. However, the SDA has a high data requirement, and needs the national or regional input-output tables, which are not readily available for Japan. In contrast, the IDA has a relatively low data requirement and can allow more detailed temporal, and national or regional studies[66,67]. Furthermore, the IDA offers advantages when analyzing spatial and time-series data[68], with popular IDA methods including the IPAT model[69], Kaya identity[70,71], the Laspeyres decomposition method and the Divisia index methods[72]. Based on extended Kaya identity, the Logarithmic Mean Divisia Index (LMDI) decomposition method has been developed[65,66,73,74], which is more adaptable and better suited to interpret results. Due to its robustness the LMDI method has been widely applied[4,6,31,32], including to decompose the intensity of energy-related CO_2 emissions at provincial level[68], decompose transport-related emissions at regional level[75], decompose emission drivers at regional level[76], and decompose emission drivers at the urban level[77].

To understand the factors shaping carbon emissions patterns at the regional level, we apply the LMDI method to elicit the effect of ten driving forces, namely (a) population, (b) per capita GDP, (c) economic structure (GDP share of each economic sector), (d) energy intensity, (e) energy mix of coal use, (f) energy mix of natural gas use, (g) energy mix of oil use, (h) emission intensity of coal, (i) emission intensity of oil products, and (j) emission intensity of natural gas.

First, we use Eq. (4) to estimate the effect of the above-mentioned driving forces of carbon emissions (EM), firstly, we present carbon emissions for each region r in a given year t as:

$$\begin{aligned} EM_{t,r} &= \sum_i \sum_j P_{t,r} \times \frac{GDP_{t,r}}{P_{t,r}} \times \frac{GDP_{i,t,r}}{GDP_{t,r}} \times \frac{EN_{i,t,r}}{GDP_{i,t,r}} \times \frac{EN_{j,i,t,r}}{EN_{i,t,r}} \times \frac{EM_{j,i,t,r}}{EN_{j,i,t,r}} \\ &= \sum_i \sum_j P_{t,r} \times A_{t,r} \times G_{i,t,r} \times I_{i,t,r} \times S_{i,j,t,r} \times C_{i,j,t,r} \end{aligned} \quad (4)$$

where i,j, t and r refer to the economic sector, fuel type, year and region as outlined above; $P_{t,r}$ and $GDP_{t,r}$ are the population and the gross domestic product for year t in region r; $GDP_{i,t,r}$ is the value-added of economic sector i for year t in region r; $EN_{i,t,r}$ is the total energy consumption for economic sector i in region r; and $EN_{j,i,t,r}$ denotes the same as above but only considering the thermal value generated from the combustion of fuel type j. For convenience we use the following notations: $A_{t,r} = \frac{GDP_{t,r}}{P_{t,r}}$ as the per capita GDP in region r for year t that is a measure of economic growth; $G_{i,t,r} = \frac{GDP_{i,t,r}}{GDP_{t,r}}$ as the share of total GDP of sector i that represents the economic structure; $I_{i,t,r} = \frac{EN_{i,t,r}}{GDP_{i,t,r}}$ as the energy intensity in sector i that is a measure of energy efficiency; $S_{i,j,t,r} = \frac{EN_{j,i,t,r}}{EN_{i,t,r}}$ as the share of fuel type j in sector i that indicates the energy mix; $C_{i,j,t,r} = \frac{EM_{j,i,t,r}}{EN_{j,i,t,r}}$ as the carbon emission coefficient of fuel type j in sector i that indicates the emission intensity.

Second, we use Eq. (5) to estimate the change of carbon emission for each region r, from the year 0 to year t ($\triangle EC_r$) as:

$$\triangle EC_r = EM_{t,r} - EM_{o,r} \quad (5)$$

According to Eq. (2), $\triangle EC_r$ consists of $\triangle P_r$, $\triangle A_r$,$\triangle G_r$, $\triangle I_r$, $\triangle S_{j,r}$ and $\triangle C_{j,r}$, which are defined respectively as a population effect, economic growth effect, economic structure effect, energy intensity effect, energy mix effect ($j = 1$, 2, 3 for coal, crude oil and natural gas, respectively) and carbon emission coefficient effect (j = 1, 2, 3 for coal, crude oil and natural gas, respectively).

Considering the above, the relationship can be expressed as follows:

$$\triangle EC_r = \triangle P_r + \triangle A_r + \triangle G_r + \triangle I_r + \sum_j \triangle S_{j,r} + \sum_j \triangle C_{j,r} \tag{6}$$

Third, we employ the additive LMDI method to estimate the effect of the ten drivers of energy-related carbon emissions in each region of Japan. The different effects are estimated through the following equations:

$$\triangle P_r = \sum_i \sum_j L(w^t_{i,j,r}, w^0_{i,j,r}) ln\left(\frac{P_{t,r}}{P_{0,r}}\right) \tag{7}$$

$$\triangle A_r = \sum_i \sum_j L(w^t_{i,j,r}, w^0_{i,j,r}) ln\left(\frac{A_{t,r}}{A_{0,r}}\right) \tag{8}$$

$$\triangle G_r = \sum_i \sum_j L(w^t_{i,j,r}, w^0_{i,j,r}) ln\left(\frac{G_{i,t,r}}{G_{i,0,r}}\right) \tag{9}$$

$$\triangle I_r = \sum_i \sum_j L(w^t_{i,j,r}, w^0_{i,j,r}) ln\left(\frac{I_{i,t,r}}{I_{i,0,r}}\right) \tag{10}$$

$$\triangle S_{j,r} = \sum_i L(w^t_{i,j,r}, w^0_{i,j,r}) ln\left(\frac{S_{i,j,t,r}}{S_{i,j,0,r}}\right) \tag{11}$$

$$\triangle C_{j,r} = \sum_i L(w^t_{i,j,r}, w^0_{i,j,r}) ln\left(\frac{C_{i,j,t,r}}{C_{i,j,0,r}}\right) \tag{12}$$

where, $L\left(w^t_{i,j,r}, w^0_{i,j,r}\right)$ is a weighting factor called the logarithmic mean weight defined as:

$$L\left(w^t_{i,j,r}, w^0_{i,j,r}\right) = \begin{cases} \frac{(EM_{i,j,r})^t - (EM_{i,j,r})^o}{ln(EM_{i,j,r})^t - ln(EM_{i,j,r})^o}, (EM_{i,j,r})^t \neq (EM_{i,j,r})^o \\ (EM_{i,j,r})^t, (EM_{i,j,r})^t = (EM_{i,j,r})^o \\ 0, (EM_{i,j,r})^t = (EM_{i,j,r})^o = 0 \end{cases} \tag{13}$$

Data availability

Data for the different economic sectors are collected and aggregated from 23 sub-sectors from the Agency of Natural Resource and Energy of Japan at prefectural level (https://www.enecho.meti.go.jp/statistics/energy_consumption/ec002/). Other socio-economic variables for each region, such as industrial value added, regional population, and regional GDP are collected from the Annual Report on Prefectural Accounts of the Cabinet Office (https://www.esri.cao.go.jp/en/sna/kakuhou/kakuhou_top.html) for the appropriate prefecture and year. GDP values are converted to standard price, namely 2011 Japanese Yen constant price. The emission dataset used for this paper can be found freely available at the Figshare data repository[78] (10.6084/m9.figshare.14472534).

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Author contributions
Y. Long. and Y. Yoshida designed this study. Y. Long and collected the data, conducted the analysis, and interpreted the results with input from H. Zheng and Q. Liu. Y. Long and A. Gasparatos wrote and revised the paper. A. Gasparatos, D. Guan, and Y. Li supervised this study.

Competing interests
The authors declare no competing interests.

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