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Research paper

How and why did fossil fuel use change in Fukushima Prefecture before and after the Great East Japan Earthquake?

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ABSTRACT

The Great East Japan Earthquake (GEJE) in March 2011 greatly changed the spatial pattern of energy use in Fukushima Prefecture. The previously nuclear-reliant energy policy has transformed, with energy now generated mainly by fossil fuels and renewable sources. The spatio-temporal variation of fossil fuel use and the major causes of these changes have not previously been fully clarified.

This study quantified the annual fossil fuel use in eight user sectors at high spatial resolution using a bottom-up approach. The total fossil fuel use in Fukushima is estimated to have increased by about 91,233 TJ from 2010 to 2015, despite decreases in most socioeconomic indicators. The increase was mainly attributed to changes in electricity generation (104,521 TJ). The three sectors with the greatest decrease in energy use were road transportation (-7159 TJ), industrial and commercial (-3608 TJ), and residential (-2334 TJ). Spatial analysis using high-resolution maps identified areas of increased energy use mainly in central, southeastern, and northeastern Fukushima and confirmed some local variations in energy use by sector. It showed that decreasing energy use in the area within 20 km of the Fukushima Daiichi Nuclear Power Station resulted in increased use in areas located >20 km from the power station. Sensitivity analysis clarified the relations among factors underlying each sector's changing energy use before and after the GEJE. For instance, consider the electricity generation sector: reduced energy use was caused by decreased energy use intensity (-23,299 TJ) and the increased use of biomass (-4848 TJ), whereas increases were caused by rising utilization efficiency (102,410 TJ) and increased electricity generation capacity (35,988 TJ), which led to a large overall increase for this sector (104,521 TJ). However, road transportation's negative energy use change (-7159 TJ) arose owing to decreased traffic volumes (-7573 TJ) and decreased energy use intensity (-7177 TJ), despite some positive energy use changes caused by the increased proportion of large vehicles (3684 TJ) and changes in mean travel speed (1381 TJ). The approach used in this study will be helpful for policy makers to evaluate spatio-temporal variations and develop policies to reduce energy use in response to unusual local events.

1. Introduction

The Great East Japan Earthquake (GEJE) of March 2011 triggered a devastating tsunami, which damaged the Fukushima Daiichi Nuclear Power Station (FDNPS) (Eisler, 2012). The disaster's socioeconomic and environmental impacts went beyond Japan. Global public acceptance of nuclear energy saw a marked decline (Kim et al., 2013). Global concerns about energy security led to increased investment in liquefied natural gas projects around the world (Hayashi and Hughes, 2013).

This incident was a turning point for Japan's overall energy policy. In 2010, the year before the GEJE, nuclear energy accounted for about 25.1% of Japan's electricity generation; this dropped to 1.5% in 2012 (Agency for Natural Resources and Energy, 2020). The replacement of Japan's nuclear power plants made the country more dependent on imports of fossil fuels (Taghizadeh-Hesary et al., 2017; Aruga, 2020). Renewable energy is clean with low carbon dioxide (CO_2) emissions, especially considering whole life cycle circulation (Chuah et al., 2015). It is strongly promoted as an alternative to fossil fuels to mitigate their associated escalating greenhouse gas and pollutant emissions (Chuah et al., 2017). Kharecha and Sato (2019) reported that CO_2 emissions by fossil fuel electricity generation increased after the GEJE until 2013, but decreased thereafter as Japan increased

Abbreviations: GEJE, Great East Japan Earthquake; FDNPS, Fukushima Daiichi Nuclear Power Station; CO_2, Carbon dioxide

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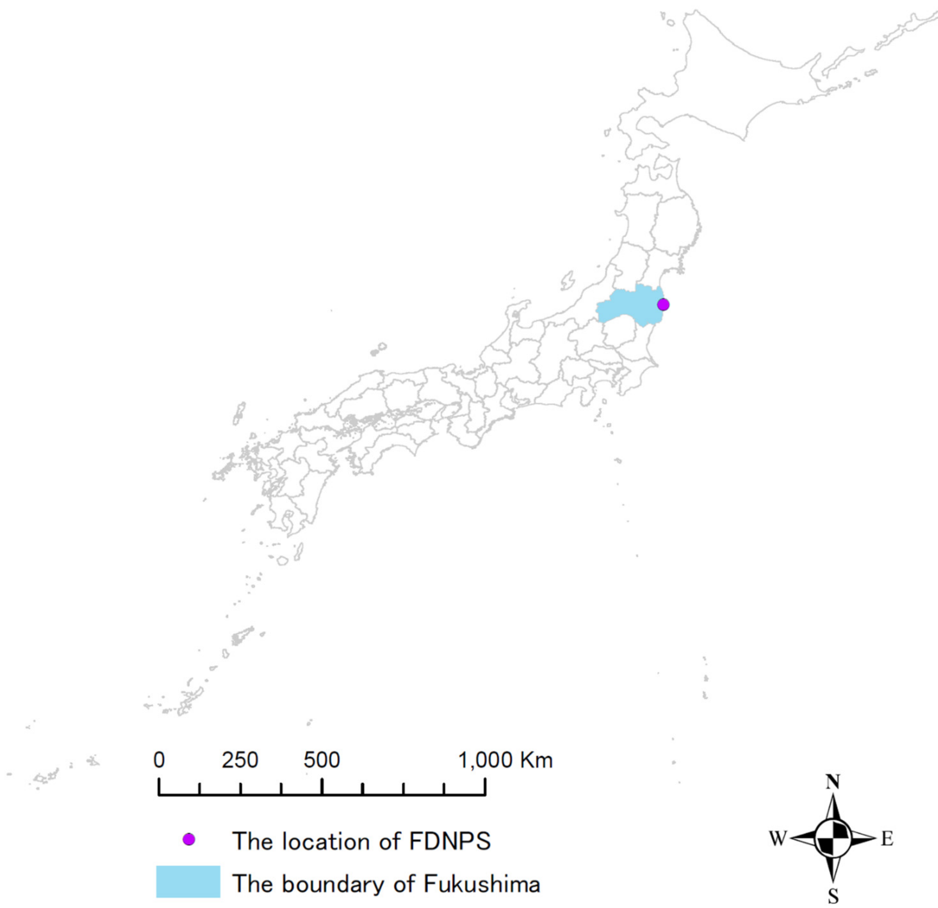

Fig. 1. The location of the FDNPS and Fukushima Prefecture in Japan.. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

renewable energy production and lowered total energy use. Energy use within Fukushima Prefecture also changed greatly since the earthquake, with the number of renewable energy facilities and their total capacity significantly increasing (Cong and Gomi, 2020). How did fossil fuel use change as a result of the GEJE? Answering this question requires quantification of energy use in the years before and after the GEJE and clarifying its spatial distributions.

Some areas are still designated as special areas for decontamination owing to the high-level radioactive contamination from the FDNPS disaster (Ministry of the Environment, 2020). The displacement of the original residents and workers to other areas of the city or outside Fukushima has reduced local energy use. Concurrently, efforts to decontaminate soils and to reconstruct damaged areas have significantly increased local energy use. These local activities in response to the GEJE seem to have affected energy use in multiple sectors. Why did energy use change in response to the GEJE? Answering this question requires qualitative and quantitative analysis of the changes related to each sector.

Top-down (downscale) approaches are often used to assess energy use or greenhouse gas emissions at a high spatial resolution by allocating totals to a high-resolution mesh level (surrogates/proxies associated with energy use activity). Lerner et al. (1988) developed a global high-resolution database of methane emissions from animals by using animal population distribution as a spatial proxy. Andres et al. (1996) made a global high-resolution database of CO_2 emissions from fossil fuel use and cement manufacture by allocating emissions into a population distribution map. In (Ghosh et al., 2010; Oda and Maksyutov, 2011) authors allocated global CO_2 emissions into a high-resolution mesh based on night light maps supplemented with other databases. On the other hand, bottom-up approaches are mainly used to map totals for a single sector. Heiple and Sailor (2008) mapped the hourly energy use from residential and commercial sectors at the level of individual tax lot or parcel in Houston, TX, by using building energy simulations and spatial data. Residential energy end use (Min et al., 2010) and household carbon footprints (Jones and Kammen, 2014) in the United States have been modeled at zip code level based on energy use intensity and spatial data. Nelson et al. (2012) optimized least-cost expansions of generation, storage, and transmission capacity for North America using data with high temporal and spatial resolution and estimated power sector emission reductions by 2030 under various policy and cost scenarios. Morris et al. (2012) presented a system that estimated average traffic fuel economy, CO_2, and other pollutant emissions by combining high-resolution real-time traffic data with instantaneous emission models. Gately et al. (2015) developed a high-resolution inventory of annual on-road CO_2 emissions for the United States based on roadway-level traffic data. Given that top-down studies include larger uncertainties in capturing the spatial patterns of activities (Gately and Hutyra, 2017), a bottom-up approach is chosen here to capture the spatial changes of local energy use. Understanding the fluctuations in energy use across the spatial distribution of these localized activities requires quantification of regional energy use at a spatially explicit level. Rather than using traditional municipality-level studies, assessing energy use at high resolution (e.g., for an individual industrial facility, road, or city block) could help clarify

Fig. 2. Conceptual framework of spatial analysis of energy use by user type in Fukushima Prefecture before and after the GEJE.

areas with the highest potential for energy use reduction and so inform process-based reduction policies.

Unlike previous high-resolution studies, this study aims to not only track local energy use for multiple sectors at high spatial resolution but also to evaluate the impacts of factors causing changes to inform detailed mitigation policies. To help policymakers decrease energy use, the major factors influencing changes in energy use of each sector have to be clarified. Many factors affect each sector's energy use and the changes in use as a result of the GEJE. When considering the impact of a certain factor that changed due to the earthquake, the other factors must be kept constant before and after the GEJE. Sensitivity analysis is applied here to measure the extent to which results are affected by changes in methods, models, values of unmeasured variables, or assumptions (Schneeweiss, 2006).

To answer the above two questions, this study first quantifies fossil fuel use in Fukushima Prefecture by sector at a local scale by a bottom-up approach to track the spatio-temporal variation of energy use at multiple resolutions before and after the GEJE and to conduct a sensitivity analysis of the major factors influencing those changes. This case study could also help policymakers in other nations conduct spatio-temporal analysis of regional energy use, explicitly observe changes of energy use due to special events, determine the major factors underlying those changes, and make process-based mitigation policies.

2. Methodology

2.1. Study area and framework for quantifying fossil fuel changes in response to the GEJE

Fukushima Prefecture is the third largest in Japan. Its 13,783.9 km^2 area had a population of 1,859,220 in 2019 (Fukushima Prefecture, 2019). The purple dot in Fig. 1 shows the FDNPS in the east of the prefecture (blue area).

This work focused on quantifying fossil fuel ('energy' hereinafter) use in the prefecture before and after the GEJE, and used the modeling framework described in Fig. 2. Our multi-resolution energy modeling calculated energy use on an individual user basis in a bottom-up manner, rather than using aggregating efforts. Energy use was spatially distributed as verified latitude and longitude coordinates (mainly for point users) and spatially explicit geolocation data (for linear and area users).

The total energy use before the GEJE was calculated for 2010 using the best available locally collected data. Those after the GEJE were estimated for 2015. Sectors using energy included electricity generation, civil aviation, waterborne navigation, waste incineration, road transportation, residential, industry and commerce, and agricultural machinery. Table 1 summarizes energy-using sectors, spatial information, activity data, and energy use intensities used here. To ensure the accuracy of estimates, the activity, spatial data, and energy use intensity data are always for the same year, and the same data sources and calculation approaches are used for the corresponding years.

2.2. Point users

Point users of energy include sites of electricity generation, civil aviation, waterborne navigation, and waste incineration (Table 1). For electricity generation, the energy use by power plants in Fukushima before and after the GEJE was calculated as follows:

$$E_{pp} = \sum_{m}^{12} \sum_{i} P_i \times h_m \times R_m \times \frac{e_m}{W_m}, \tag{1}$$

where E_{pp} is the annual energy use (MJ) by power plants in Fukushima in 2010 or 2015; P_i is the electricity generation capacity (kW) of power plant i in each year; h_m is the hours (h)

Table 1
Spatial data used for identifying energy users and other data used for quantifying energy use for each sector in Fukushima.

Sector	User type	Spatial information	Activity data	Energy use intensity
Electricity generation	Point	Center points of chimneys of power plants (latitude, longitude)	Capacity and generation types of fossil-fuel power generation and running ratios of power plants in 2010 and 2015	Energy use intensities of fossil-fuel power generation in 2010 and 2015
Civil aviation	Point	Representative points of runways at airports (latitude, longitude)	Monthly flight numbers in 2010 and 2015, aircraft types, engine types, number of engines	Energy use intensity of aircraft by engine type
Waterborne navigation	Point	Representative points of buildings at ports (latitude, longitude)	Load factors, fuel use time, and monthly trips by vessels in 2010 and 2015	Energy intensities of vessels by type and mode
Waste incineration	Point	Center points of chimneys at waste incineration plants (latitude, longitude)	Combustion agent use rate and municipal solid waste combustion amount in 2010 and 2015	Energy intensities of combustion agents by incineration type in 2010 and 2015
Road transportation	Line	Gridded total road length (km) by road-width category from road density mesh	Traffic conditions in 2010 and 2015, road lengths from road density mesh 2010, and administrative map of Fukushima in 2010 and 2015	Energy intensities of vehicles by travel speed, type, and models for 2010 and 2015
Industrial and commercial	Area	Area (km^2) and number of workers in economic census areas	Regional energy use in 2010 and 2015 and mesh of census areas on worker numbers in 2009 and 2014	Energy intensities of workers by industry category in 2010 and 2015
Residential	Area	Area (km^2) and number of households in population census areas	Mesh of census areas for household numbers in 2010 and 2015	Energy intensities of households by building type and occupancy in 2010 and 2015
Agricultural machinery use	Area	Area of cultivated lands by crop type in agricultural census areas (ha)	Mesh of census areas for cultivated land in 2015 by crop type	Energy intensity of farmland by crop type

operating at full power in month m; R_m is the mean utilization efficiency (%) of fossil-fueled power plants in month m of each year; e_m is the total energy use (MJ) by fossil-fueled power plants in Tohoku region in month m of each year; W_m is the total electricity generated (kWh) in month m of each year. The capacities of power plants in Fukushima were those listed on the websites of the operating companies and a database (Electrical Japan, 2017). The monthly utilization efficiency, total energy used for electricity generation (including the related kinds of coal, oil, and gas fuels), and the total amount of electricity generated are reported by power plant operators and published by the government of Japan each year (Agency for Natural Resources and Energy, 2016a).

Civil aviation energy use included passenger and cargo aircraft during landing and take-off (LTO) at airports and helipads. Their energy use before and after the GEJE was calculated as follows:

$$E_{ah} = \sum_{i,a} N_{i,a} \times F_a \times H, \tag{2}$$

where E_{ah} is the annual energy use (MJ) by all aircraft in 2010 or 2015; $N_{i,a}$ is the number of annual departures and arrivals of type a aircraft in each year at site i; F_a is the energy use intensity of type a aircraft (kg LTO^{-1}); H is the energy coefficient of the aircraft fuel (jet fuel; MJ kg^{-1}). Information on aircraft type (Flugzeuginfo, 2017) and monthly flight records of all aircraft in both years were collected from relevant websites (Fukushima Prefecture, 2020; Doctor-Heli, 2020). The energy use intensity data were from relevant databases for airplanes (European Union Aviation Safety Agency, 2017) and helicopter emissions (Federal Office of Civil Aviation, 2013).

Energy used in waterborne navigation included that by vessels during round trips to ports in Fukushima. The energy use before and after the GEJE was calculated as follows:

$$E_v = \sum_{i,j,p,q} NV_{i,j} \times h_{j,p,q} \times F_{j,p,q} \times L_{j,p,q} \times H, \tag{3}$$

where E_v is the annual energy use (MJ) by vessels during round trips to ports in 2010 or 2015; $NV_{i,j}$ is the annual number of vessels of type j (merchant, car ferries, evacuated, fishing, or other) traveling to port i in each year; $h_{j,p,q}$ is the operating hours (h) by engine type q (main engine, auxiliary engine, of assistance boiler) in type j vessels in mode p (traveling, mooring, or loading and unloading) to or at port; $F_{j,p,q}$ is the fuel use intensity (kg h^{-1}) by vessel type, engine mode, and engine type; $L_{j,p,q}$ is the load factor (%) by vessel type, engine mode, and engine type; H is the energy coefficient of the vessels' fuel (heavy oil A, diesel oil; MJ kg^{-1}). Statistical data on vessels in ports provided information on vessels' annual trips (Statistics Japan, 2020a). The related parameters for vessels in different modes were extracted from technical reports (Ocean Policy Research Institute, 2007; Ministry of the Environment, 2018). The mean traveling distance was assumed to be 1 km in traveling mode to derive the operating hours.

Energy use in waste incineration included that in the form of combustion agents ("city gas" comprising liquid petroleum gas and natural gas). Its amount before and after the GEJE was calculated as follows:

$$E_{ip} = \sum_{i} AW_i \times \frac{b}{c} \times H, \tag{4}$$

where E_{ip} is the annual energy use (MJ) of the combustion agent (city gas) during waste combustion at incineration plants in 2010 or 2015; AW_i is the total amount of waste (t) incinerated annually at plant i; H is the energy coefficient of fuel (city gas; MJ kg^{-1}); b is the volume (m^3) of combustion agent used at waste incineration plants in Tokyo each year; c is the amount of waste (t) incinerated in Tokyo each year. The amounts of waste incinerated for both years were extracted from reports on municipal solid waste (Ministry of the Environment, 2017). Due to lack of data, the annual usage of combustion agents and the related amounts of waste incinerated in Tokyo (Clean Authority of Tokyo, 2020) were used to derive the use rate of a combustion agent, which was substituted for waste combusted in Fukushima.

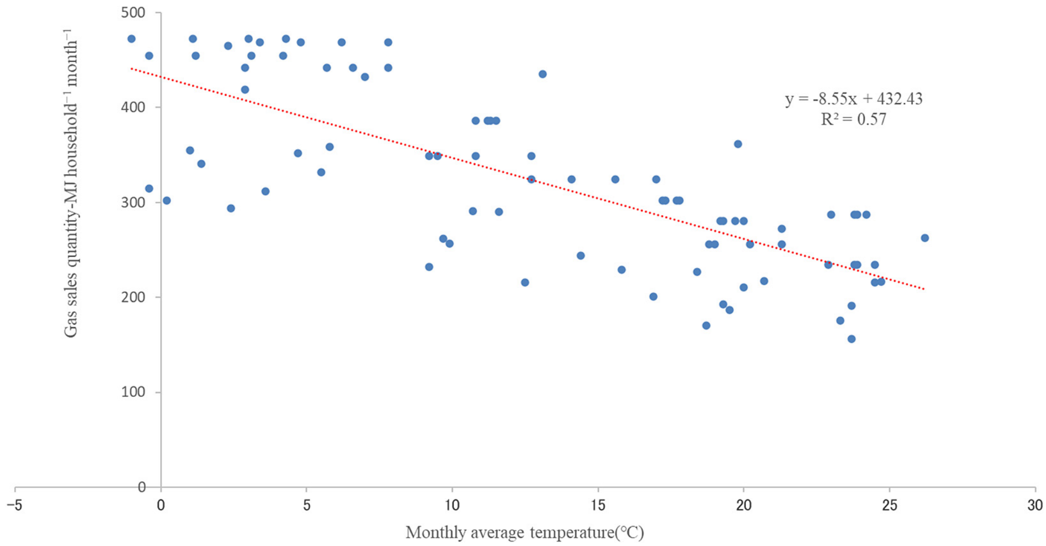

Fig. 3. Sensitivity of gas sales per household (MJ household^{-1} month^{-1}) to monthly average temperature (°C) across seven cities in Fukushima Prefecture.

2.3. Linear energy users

Linear energy users comprised vehicles on roads. Data came from traffic censuses compiled by the Ministry of Land, Infrastructure, Transport and Tourism for each prefecture every five years, with the latest being in 2015. The census data include road information (name, width, length, number of lanes, and classification for each road segment), hourly and daily traffic volumes, and 12-h mean daytime vehicle speeds for small vehicles (light passenger cars, regular passenger cars, light trucks, and small freight cars) and large vehicles (buses, regular trucks, and special-use vehicles). Their energy use before and after the GEJE was calculated as follows:

$$E_c = \sum_{s}^{59} \sum_{i,o,t} V_{i,o,s,t,v} \times l_{i,o,s} \times d \times F_{t,v} \times H, \qquad (5)$$

where E_c is the annual energy use (MJ) by vehicles on roads in 2010 or 2015; $V_{i,o,s,t,v}$ is the daily traffic volume (number of vehicles) and speed v of type t vehicles on roads of width category o from grid (cell) i belonging to municipality s in each year; $l_{i,o,s}$ is the gridded total length of roads (km) of width-category o in grid i belonging to municipality s; d is the number of days in each year; $F_{t,v}$ is the fuel use intensity of type t vehicles at speed v (liter km^{-1} vehicle^{-1}); H is the energy coefficient of vehicle fuel (gasoline, diesel oil; MJ liter^{-1}).

Traffic volumes and travel speeds were taken from the Traffic Censuses of 2010 and 2015 (Ministry of Land, Infrastructure, Transport and Tourism, 2017). The energy use intensity by vehicle type and travel speed were extracted from experimental results on emission factors for different models of vehicles on the road (Dohi et al., 2012). Data for 2005–2009 models were used in the calculation for 2010, and data for 2011–2014 models were used for the 2015 calculation. Due to a lack of road data for 2015, the 2010 road density mesh was used for both years. To count the energy use by vehicle on roads, the mean traffic volume and travel speed observed from the traffic censuses of 2010 and 2015 were substituted for all roads in the same municipality by the six road-width categories. Using Formula (5), we counted and mapped the energy use from roads on 9268 cells for both years.

2.4. Area energy users

Energy use by the residential, industrial and commercial, and agricultural sectors was modeled as occurring across certain areas. Residential energy use before and after the GEJE was calculated as follows:

$$E_h = \sum_{m}^{12} \sum_{b,f,i} NH_{b,f,i} \times I_{b,f,m}, \qquad (6)$$

where E_h is the annual energy use (MJ) by households from population census areas in 2010 or 2015; $NH_{b,f,i}$ is the number of households with occupancy f (four categories: 1, 2, 3, or ≥4 persons) living in building type b in grid i in each year; $I_{b,f,m}$ is the energy use intensity (MJ household^{-1} month^{-1}) of households by occupancy and building type in month m of each year.

The number of households in each grid (30 arcsec in latitude, 45 arcsec longitude, equivalent to approximately 1 × 1 km resolution) are extracted from the population census (Statistics Japan, 2017). The monthly energy use intensity for Tohoku region including city gas, liquid petroleum gas, and kerosene were summarized from a nationwide survey of household energy use and emissions (Statistics Japan, 2016). Based on the monthly temperature (Japan Meteorological Agency, 2020) and quantitative gas sales reported by local gas companies, temperature sensitivities were derived for seven cities in 2015 (Fig. 3). The regional values were adjusted for seven sub-regional areas in Fukushima Prefecture before and after the GEJE based on monthly temperatures in each year. Formula (6) calculated residential energy use for 6867 grid areas in the 2010 census and 5338 grid areas in the 2015 census. There were fewer residential grids in 2015 than in 2010 due to emigration to other areas and prefectures.

Industrial and commercial energy use included that consumed by workers. Totals before and after the GEJE were calculated as follows:

$$E_{ic} = \sum_{k}^{18} \sum_{i} C_{i,k} \times \frac{e_k}{w_k}, \qquad (7)$$

where E_{ic} is the annual energy use (MJ) in 2010 or 2015 by workers; $C_{i,k}$ is the number of workers in category k (see definitions by Ministry of Internal Affairs and Communications, 2013) in grid i

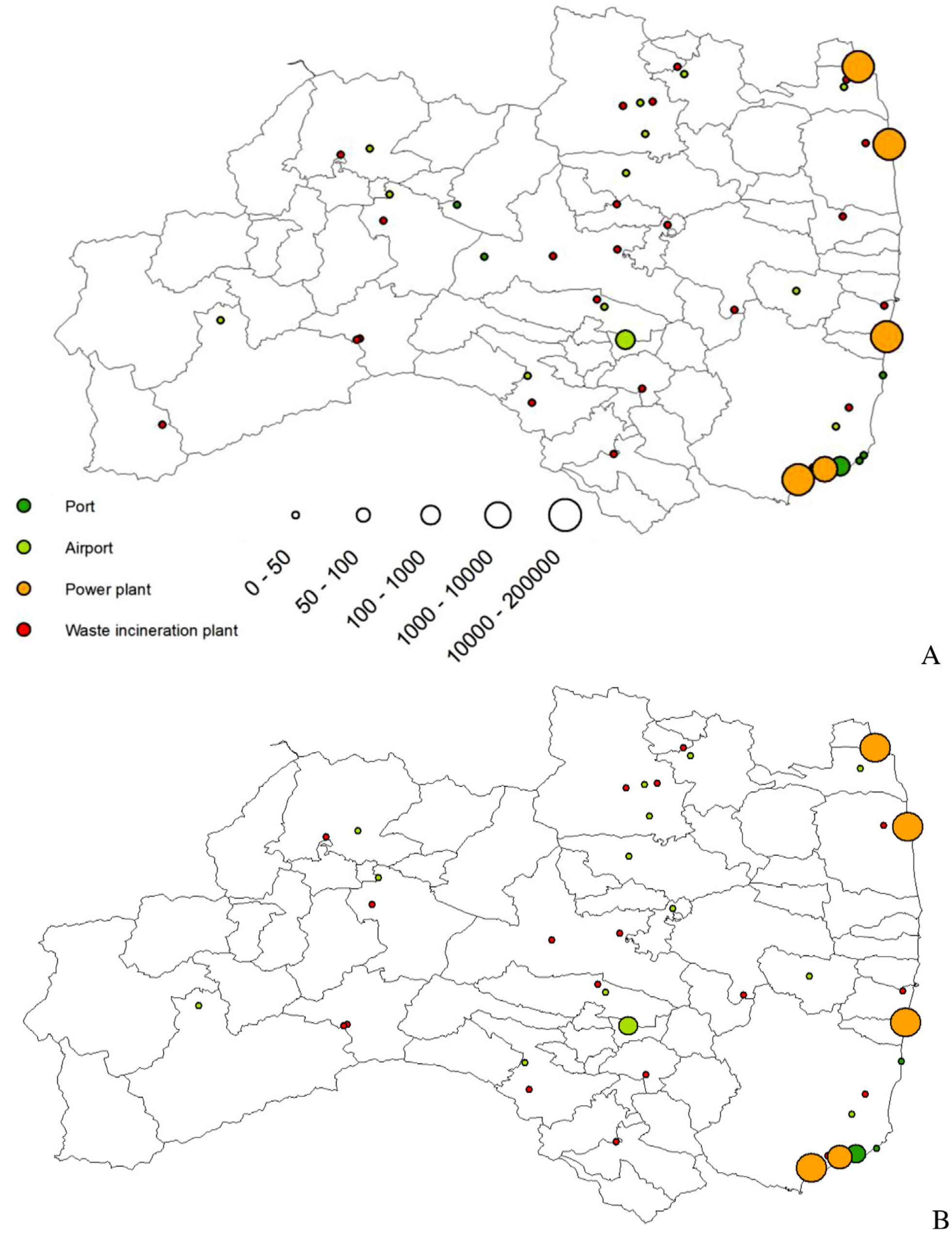

Fig. 4. Point energy users in Fukushima (A) in 2010 (n = 50), (B) in 2015 (n = 47), unit: TJ yr^{-1}.

in each year; e_k is the total annual energy use (MJ) by category in each category; and w_k is the total number of workers by category in each year.

The numbers of workers in each grid were extracted from the economic census (Statistics Japan, 2017). Energy use intensities (including all kinds of coal, oil, and gas fuels) for 18 categories were derived from the annual total energy use of each category (Agency for Natural Resources and Energy, 2017) and the total number of workers (Statistics Japan, 2017). Formula (7) was used to calculate the energy use from 5094 economic census grid areas in 2010 and from 4630 grid areas in 2015.

Agricultural machines used energy during crop planting. Their energy use before and after the GEJE was calculated as follows:

$$E_{am} = \sum_{i,c} A_{i,c} \times F_c \times H, \tag{8}$$

where E_{am} is the machines' annual energy use (MJ) for planting crops on farmland in all census areas in 2010 or 2015; $A_{i,c}$ is the area (ha) planted with crop c in grid i in each year; F_c is the fuel use intensity for crop type c (liter ha^{-1}); H is the energy coefficient of machine-used fuel (gasoline, diesel oil, kerosene, and heavy oil A; MJ $liter^{-1}$). The grid areas planted with each crop were obtained from the agricultural and forestry census (Statistics Japan, 2017). Energy use intensities were derived from a technical report (National Institute for Agro-Environmental Sciences, 2003) and an academic paper (Shimizu and Yuyama, 2007).

Formula (8) was used to calculate energy use in 7649 grid areas in the 2010 census and in 6764 grids in 2015.

2.5. Data integration

The calculations and mapping of energy use by each sector were integrated using ArcGIS v. 10.4. The original multi-resolution maps were converted to a mesh (30 arcsec in latitude,

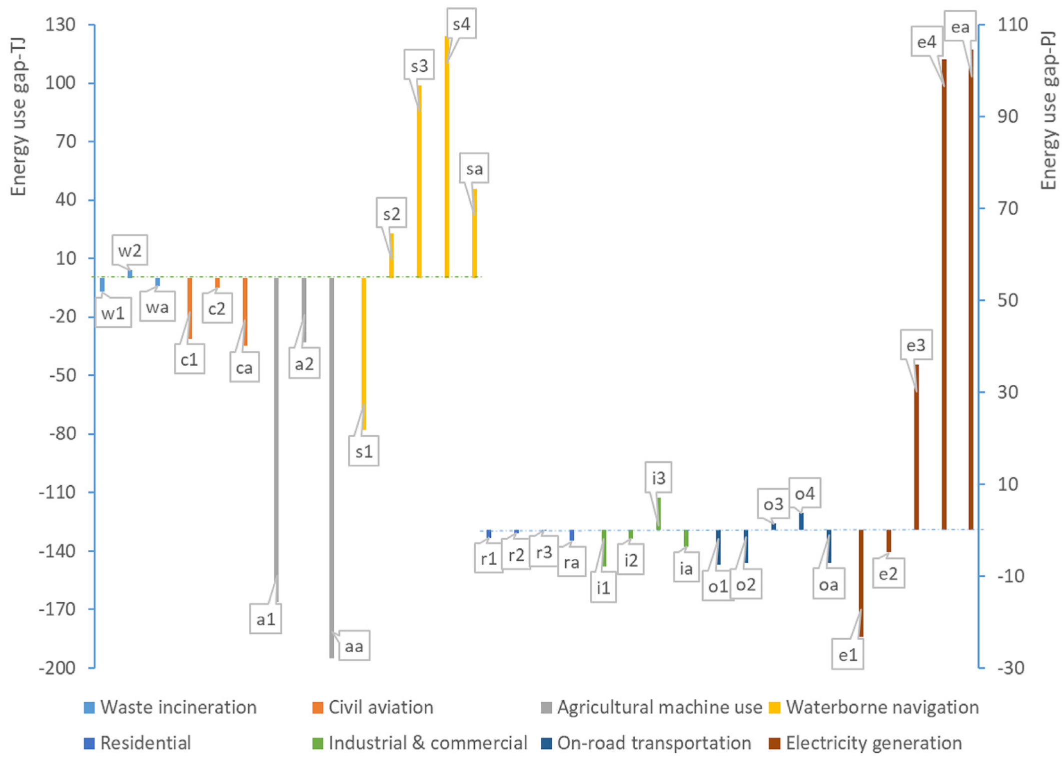

Fig. 5. Sensitivity analysis results for factors affecting energy use gap (2015 values– 2010 values) by sector. The right *y*-axis refers to residential, industrial and commercial, on-road transportation, and electricity generation sectors (unit: PJ). Negative values imply negative impacts on energy use gap. Note: contributing factors for waste incineration: w1 (decreased usage rate of combustion agent), w2 (increased incineration amount); civil aviation: c1 (decreased number of departures), c2 (changed aircraft types); agricultural machine use: a1 (decreased total planted area), a2 (changed crop mix); waterborne navigation: s1 (decreased number of trips), s2 (increased proportion of international trips), s3 (increased mean gross tonnage per vessel to each port by vessel type), s4 (changed proportions of vessel types); residential: r1 (decreased total number of households by building and occupancy type in seven subregions), r2 (decreased percentage of multi-occupancy households), r3 (decreased energy use intensity); industrial & commercial: i1 (decreased total number of workers), i2 (changed percentages of workers by category), i3 (changed energy use intensity by category); on-road transportation: o1 (decreased total traffic volume), o2 (decreased energy use intensity), o3 (changed mean travel speed by municipality), o4 (increased proportion of large vehicles (totals)); electricity generation: e1 (decreased energy use intensity), e2 (increased use of biomass), e3 (increased electricity generation capacity), e4 (increased utilization efficiency). Labels ending in "a" indicate overall change owing to all contributing factors.

45 arcsec longitude, approximately 1 × 1 km resolution) for convenience in data visualization and analysis.

3. Results and discussion

3.1. Changes in energy by sector and causative factors

Table 2 lists the energy use of eight sectors in Fukushima before and after the GEJE. Energy used for electricity generation increased the most (104,521 TJ) after the GEJE. During the study period, the total generating capacity of all five of the prefecture's steam power plants increased from 9481 MW in 2010 (Fig. 4A) to 10,331 MW in 2015 (Fig. 4B), the annual mean utilization efficiency increased from 43.6% in 2010 to 57.5% in 2015, the number of biomass co-firing power plants increased from 1 in 2010 to 3 in 2015, and the mean energy use intensity decreased from 13,451 in 2010 to 12,149 MJ MWh^{-1} in 2015. Sensitivity analysis can evaluate the impact that changes to each of these factors has on energy use (Schneeweiss, 2006); the difference in energy use between 2010 and 2015 was found by adjusting each factor independently between its values for each year. For example, assuming that the electricity generation capacity in 2010 changed to its 2015 value with the other factors remaining unchanged, the new energy use in 2015 was calculated and the change in energy use (Fig. 5 and Appendix A) resulting from this change alone (2015 value – 2010 value) was derived. Here, we call this change in energy use the *energy use gap*. Fig. 5 shows a positive energy use gap for electricity generation, which was mainly attributed to increased utilization efficiency, despite a change in energy intensity causing a significant negative energy use gap. These results imply that reducing the energy use intensity of electricity generation and increasing the biomass co-firing capacity could reduce the amount of fossil fuels used by power plants.

Energy used by civil aviation decreased slightly from 150 TJ in 2010 to 115 TJ in 2015. The number of departures from Fukushima Airport fell from 4879 in 2010 to 3840 in 2015, while helipad departures increased from 811 in 2010 to 843 in 2015. The types of aircraft changed due to the suspension of international flights at Fukushima Airport after the GEJE. The factor analysis results in Fig. 5 show that the negative energy use gap for civil aviation arose mainly due to the changed number of departures. Overall, decreased traffic by a changed mix of aircraft types reduced energy use in the civil aviation sector.

Energy use in waterborne navigation increased slightly by about 46 TJ from 2010 to 2015. Vessels' total gross tonnage increased from 18,942,706 to 22,443,330 t, while the number of calls to ports decreased from 14,284 to 8824 during the study period. The percentage share of the number of trips to ports by merchant, evacuated, and other vessels (with higher energy use intensity) increased, while that by fishing vessels (with lower energy use intensity) decreased due to restrictions on fishing. The percentage of vessels traveling internationally (with higher energy use intensity) increased. Factor analysis found that the positive energy use gap for waterborne navigation was mainly caused by the changed types of vessels visiting ports, despite a decrease in the total number of voyages having a negative

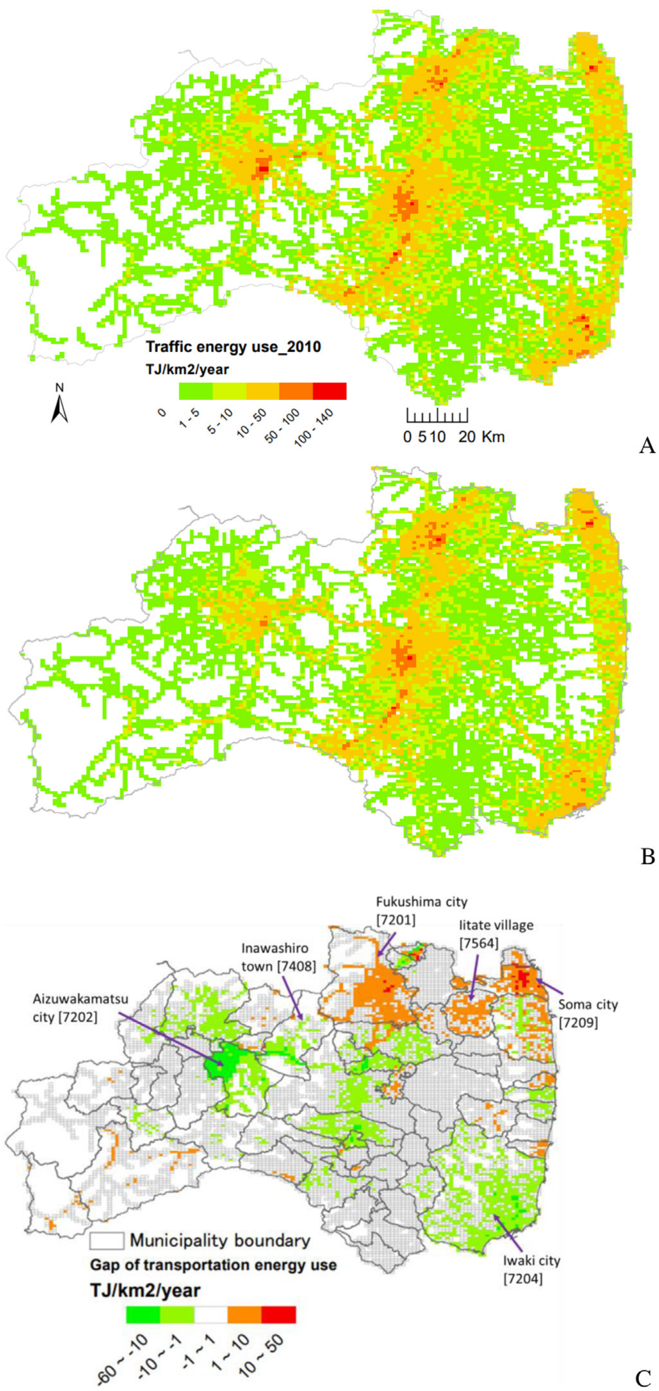

Fig. 6. Energy use for road transportation by road density mesh (resolution, ∼1 × 1 km) in (A) 2010 and (B) 2015 (same color scale as (A)). (C) Gap in energy use between 2015 and 2010 overlaid with municipality boundaries (municipality codes in square brackets). The three municipalities with the largest positive gaps are labeled, along with those with the largest negative gaps. Unit: TJ km^{-2} yr^{-1}.. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

contribution to the energy use gap. Overall, increased traffic of certain types of vessel was mostly responsible for the positive energy use gap. Decreasing the number of voyages, the proportion of voyages by vessels with high energy use intensity, and the mean gross tonnage per vessel could reduce energy use.

Waste incineration used slightly less energy (4 TJ) in 2015 than in 2010. While the number of incinerators decreased, the total amount incinerated increased from 602,457 to 640,614 t. The usage of combustion agent decreased from 72.5 to 61.3 MJ per tonne waste. Fig. 5 shows that the negative energy use gap was mainly attributable to the changed use rate of combustion agent, despite the increased amount of waste incinerated having a positive contribution to the energy use gap. Overall, decreasing the use rate of combustion agents could reduce the energy used for waste incineration.

Energy used for road transportation decreased between 2010 and 2015 by more than that for any other sector (by 7159 TJ, Table 2). Fig. 6A, B shows the spatial distributions of the energy in both years. There were mixed contributions to the energy use gap: energy use decreased mainly from northwestern to southeastern areas (green cells in Fig. 6C), while it increased mainly in northeastern and southwestern areas (red and orange cells in Fig. 6C). Based on statistics for environmental remediation (Ministry of the Environment, 2020), about 16,538 trips by 10-tonne trucks were needed to transport about 45,939 m^3 polluted soil from 43 temporary storage sites to two intermediate storage sites in 2015. The construction of new buildings in 2015 was about double that in 2011 (Statistics Japan, 2020b). The traffic census confirmed that the percentage of large vehicles (with larger energy use intensity) increased in most municipalities. These data indirectly imply that transportation associated with environmental remediation and reconstruction increased traffic energy use. The three municipalities with the most-negative energy use gaps (Aizuwakamatsu City [municipality code: 7202]; Iwaki City [7204]; Inawashiro Town [7408]) showed significant negative contributions from the daily numbers of small and large vehicles on most of the road-width categories, except category 5 (Fig. 7). On the other hand, significant increases in the daily number of vehicles and decreased speeds were found in the three municipalities with the most-positive energy use gaps (Fukushima City [7201]; Soma City [7209]; Iitate Village [7564]). Fig. 5 shows that the decreased traffic volume and the changed model of vehicles (decreased energy use intensity) caused a significant negative energy use gap. Overall, promoting new vehicle models to decrease energy use intensity and decreasing the percentage of large vehicles could help to reduce energy use.

Residential energy use decreased by about 2334 TJ from 2010 to 2015 (Table 2). Fig. 8 shows that the number of areas without residential energy use increased since the GEJE, mainly in eastern areas near the designated sites for decontamination (Ministry of the Environment, 2020). During this period, the number of households decreased by about 61,767 (Table 2 and Fig. 9). In particular, the number of multiple-occupancy households decreased; the changing numbers of occupants in both detached and collective buildings were consistent with the changes of energy use. The percentage of households with three or more occupants (with larger energy use intensity) in both building types decreased in this period. Fig. 5 shows that the negative residential energy use gap arose mainly due to the decreased total number of households in all seven subregions. The results imply that decreasing the total number of households and reducing the percentage of households (particularly detached buildings) with higher energy use intensities could mitigate energy use.

Industrial and commercial energy use decreased by about 3608 TJ from 2010 to 2015 (Table 2). Similar to the residential sector, the areas with high energy use changed little (Fig. 10), except those within 20 km of the FDNPS (designated areas for decontamination). During this period, the number of workers decreased from 943,465 to 803,372 (Table 2). The proportions of workers in manufacturing, auto power generation, transport and postal activities, wholesale and retail trade, and living-related and personal services and amusement services (with larger energy use intensity) decreased the most as inhabitants moved to other

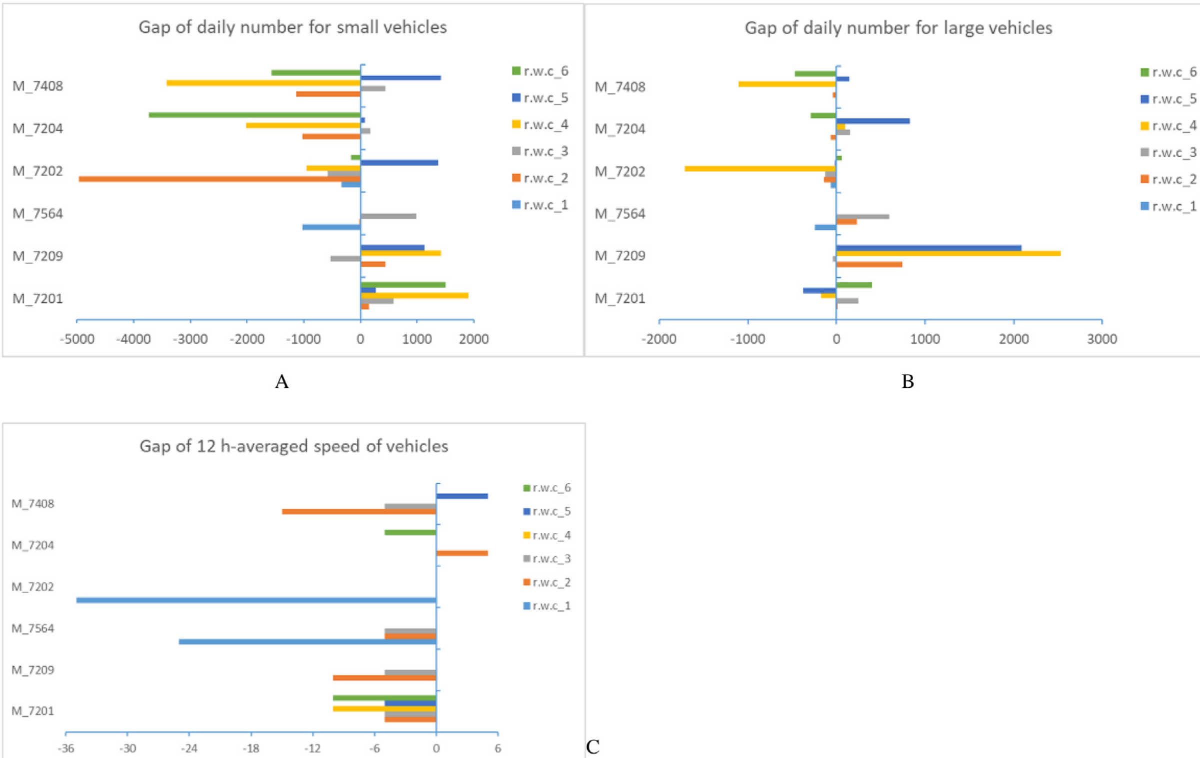

Fig. 7. Changes in traffic (A) volume of small vehicles, (B) volume of large vehicles, and (C) vehicle speed (km h^{-1}) between 2010 and 2015 by road-width category for the municipalities with the three most-positive (municipality codes: 7564, 7209, and 7201) and three most-negative energy use variations (municipality codes: 7408, 7402, and 7402). The gap was found by subtracting the 2010 data from those for 2015. Road-width category 1 (r.w.c_1) corresponds to a road narrower than 3 m; r.w.c_2 corresponds to a road width of 3–5.5 m; r.w.c_3 to 5.5–13 m; r.w.c_4 to 13–19.5 m; r.w.c_5 to 19.5–25 m; r.w.c_6 to a road width of > 25 m.

Table 2
Comparison of energy use by sector in 2010 (before the GEJE) and 2015 (after the GEJE).

Sector	Total fossil fuel use before GEJE (TJ)	Number of sources before GEJE	Total fossil fuel use after GEJE (TJ)	Number of sources after GEJE	Gap of fossil fuel use (after–before) (TJ)
Electricity generation	437,757	5 power plants	542,277	5 power plants	104,521
Civil aviation	150	14 airports	115	14 airports	−35
Waterborne navigation	478	7 ports	524	7 ports	46
Waste incineration	45	24 incineration plants	41	21 incineration plants	−4
Road transportation	94,699	9268 cells with vehicles on roads	87,540	9268 cells with vehicles on roads	−7 159
Residential	20,859	6867 cells with 791,362 households	18,525	5538 cells with 729,595 households	−2 334
Industrial & commercial	107,092	5094 cells with 943,465 workers	103,484	4630 cells with 803,372 workers	−3 608
Agricultural machine use	1 145	7649 cells had machines used for planting	951	6764 cells had machines used for planting	−195
Total	662,225		753,458		91,233

prefectures. The share of workers increased most for medical, healthcare and welfare, miscellaneous services, and government (with lower energy use intensity). Fig. 5 shows that the negative industrial and commercial energy use gap arose mainly due to changes in the total number of workers, despite their changing energy use intensity having a positive contribution. The results reflect that decreasing the total number of workers and reducing the percentage of workers in categories with large energy use intensities are effective in reducing this sector's total energy use.

Energy use by agricultural machines decreased by about 195 TJ from 2010 to 2015; the planted area also decreased, by about 12,741 m^2. Fig. 11 shows the impact of the GEJE on the energy use, with the number of areas with higher energy use (red grids) decreasing and the number of areas without energy use increasing, especially eastern areas near the designated areas for decontamination. Overall, areas planted with greenhouse tomatoes, Japanese radishes, and Japanese mustard spinach (with higher energy use intensity) decreased significantly in this period. Factor analysis showed that the negative energy use gap was mainly due to the decreased total planting area (Fig. 5). The results reflect that decreasing the total planting area and decreasing the

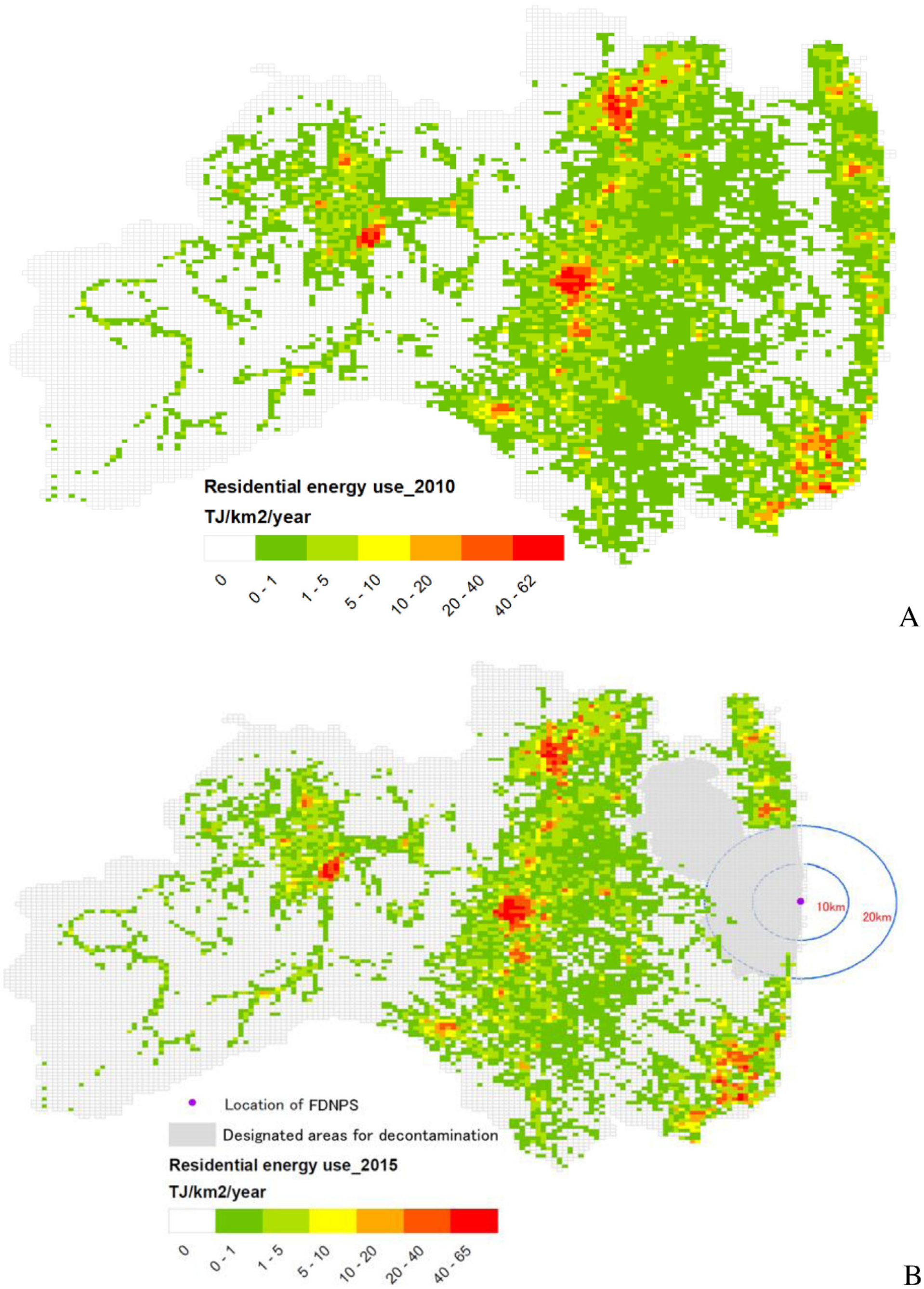

Fig. 8. Map of residential energy use from fossil fuels in (A) 2010 and (B) 2015. Unit: TJ km^{-2} yr^{-1}.

percentage of planting area for crops with higher energy use intensities could help to reduce energy use.

Changes to electricity generation produced a substantial impact on total energy use, which increased by about 91,233 TJ (or 13.8%) from 2010 to 2015. The total energy use and the energy use gap following the GEJE for all users are summarized in a mesh (Fig. 12). The overall distribution of total energy use appears similar in both years, although 2015 (Fig. 12B) has more areas with high energy use than 2010 (Fig. 12A). Fig. 12C shows that areas of significantly increased energy use are mainly located in central, southeastern, and northeastern Fukushima. On the other hand, areas of decreased use are within 20 km of the FDNPS and some inner areas. This reflects a trend of the GEJE and the designation of special areas for decontamination to have caused decreased energy use in areas around the FDNPS (within 20 km) and increased use in further areas.

3.2. Reliability and limitations of the results

Table 3 compares the energy use by residential and road transportation in 2010 and 2015 between this study and the energy balance table reported by the government Agency for Natural Resources and Energy (2017). The energy balance table estimated energy use for road transportation based on recorded fuel purchases per household and household number (Agency for Natural Resources and Energy, 2016b), rather than our use of observed traffic conditions (including vehicles from other prefectures). The government estimated residential use using per household sales

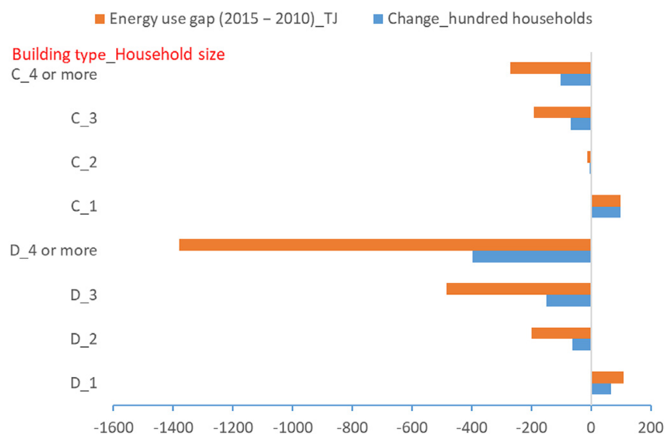

Fig. 9. Energy use gap (TJ) and changes in the numbers of households by building type from 2010 to 2015. Building type C indicates households in collective buildings, and D means those in detached buildings. Household size indicates the number of residents in each household.

Table 3
Comparison of energy use estimate between this study and the energy balance table.

Category		Residential	Road transportation
2010	This study	20,859	94,699
	Energy balance table	35,870	18,812
2015	This study	18,525	87,540
	Energy balance table	32,338	17,755
Gap	This study	−2 334	−7 159
	Energy balance table	−3 532	−1 057

data for city gas and household number for other fuels. Using resale fuel quantities and overestimated quantities of fuel purchased per household made the government's annual energy estimation greater than ours by a significant magnitude. On the other hand, both methods identified consistent negative trends in energy use for these two sectors in this period, indicating that our results were reasonable to some extent.

The assumptions and approximations used here entailed some uncertainties. For example, the utilization efficiency of power plants varies by plant and with time; however, our calculations used averaged monthly values for all plants. Our calculations for waste incineration used the averaged use rate of combustion agent (derived from incinerators in Tokyo) for all the incinerators in Fukushima. Calculations for the industrial and commercial sector used category-specific energy use intensity data at prefectural level for application at census-area level. This procedure enabled the quantification of energy use at a high spatial resolution by reducing temporospatial specificity, which needs to be improved in future work. Assuming uniform traffic conditions for a given type of road in each municipality, average traffic conditions were summarized from census data and substituted for all roads to estimate energy use. As the census mainly considered major roads, traffic volumes and energy use in each year for other roads were overestimated. Data for regional residential energy use intensity in 2010 were not available; those were derived by adjusting values for 2015 using the differences in monthly temperature between 2010 and 2015. This was done assuming constant energy use intensity by home appliances in both years, suggesting that residential energy use in 2010 was underestimated.

3.3. Policy implications

Key data used in this study are available for all Japanese prefectures and are updated regularly, making the presented method widely applicable. This analysis could help policymakers in other nations quantify spatiotemporal regional energy use, clarify trends in and major causes of change in energy use due to unique events or disasters, and improve mitigation policies in a process-based manner. This study provides a detailed bottom-up methodology for accessing local energy use by using spatially-explicit data and measured/derived energy use intensity data. If this approach is to be used in other locations, geolocated statistical data and spatio-temporally varying energy-use intensity data will be needed.

Generally, it is not easy to clarify the major positive or negative causes of changes in energy use when multiple opposing factors are acting. This study has shown that the present sensitivity analysis could identify the major factors from multiple factors acting in each sector. Therefore, it could help policymakers understand situations of this kind.

This sensitivity analysis evaluated the impact of each factor, including energy use activity and intensity data, identifying some opportunities for mitigating energy use by controlling these factors. The process followed in quantifying process-based energy use was explained using factors such as the utilization efficiency of power plants, the mode of shipping vessels, the consumption rate of incineration combustion agents, and the speeds of vehicles on roads. The analysis reveals that improving rates of waste recycling to decrease the amount of waste incineration and the accompanying consumption of combustion agents could mitigate energy use. Adjusting transportation schedules for a high loading rate of vessels could reduce the number of journeys and energy use. Controlling traffic flows to avoid congestion and ensuring optimal travel speeds on roads could reduce energy use by traffic. Adjusting industry categories, planted crop types, household size, and building type to make them use less energy could also reduce energy use in each sector.

4. Conclusions and future research

Following the GEJE (i.e., 2010 vs. 2015), total fossil fuel use across eight sectors in Fukushima increased about 91,233 TJ, despite most socioeconomic indicators showing decreasing trends. The increase was mainly attributed to changes in the electricity generation sector (104,521 TJ). Road transport (−7159 TJ), industrial and commercial (−3608 TJ), and residential (−2334 TJ) energy use all significantly decreased during this five-year period. Shutting down nuclear power plants and the concurrently increased reliance on power from fossil fuels resulted in increased energy use in electricity generation. The increased transportation of goods for reconstruction resulted in greater energy use by waterborne navigation. On the other hand, reductions in road traffic, household occupancy, numbers of workers, farmland cultivation, and facility users resulted in decreased energy use in other sectors. Spatial analysis identified areas of increased energy use mainly in central, southeastern, and northeastern Fukushima. This result suggests that decreased energy use within 20 km of the FDNPS was linked with increased use in areas located farther from the power station. High spatial resolution maps confirmed some local variations in energy use by sector, which were linked with events in Fukushima; e.g., increased use of fossil fuel in power plants as nuclear plants were closed; the designation of areas for decontamination with limits on residential, farming, and industrial and commercial use; and the removal of polluted soils from and reconstruction in the contaminated areas.

Sensitivity analysis clarified why and how related factors in each sector changed the energy use before and after the GEJE. For electricity generation (energy use gap: 104,521 TJ), the main positive contribution was increased utilization efficiency (102,410 TJ), while decreases in energy intensity constituted a significant negative contribution to the energy use gap (−23,299 TJ). Civil aviation's negative energy use gap (−35 TJ) was mainly attributed

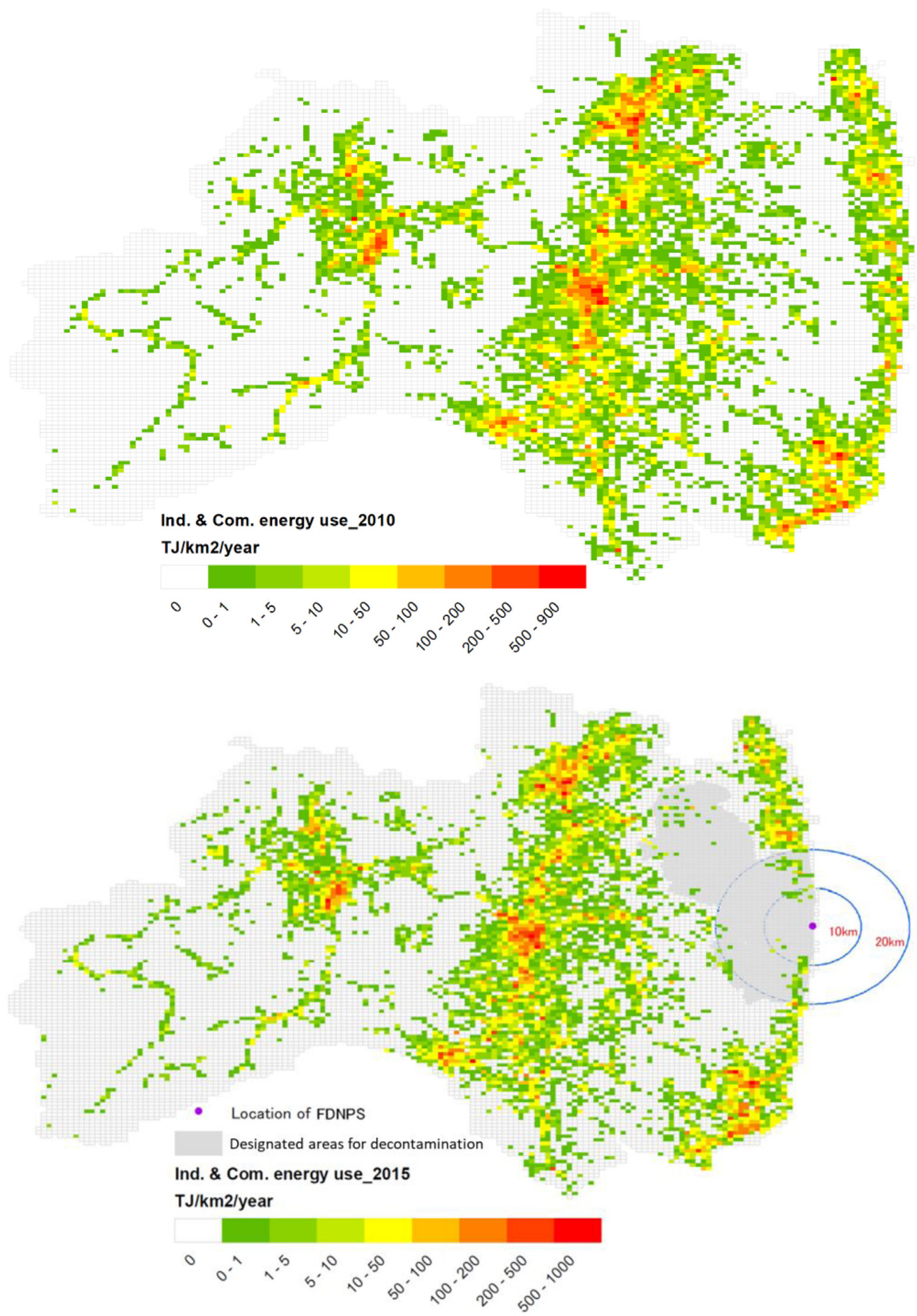

Fig. 10. Industrial and commercial energy use in (A) 2010 and (B) 2015. Unit: TJ km^{-2} yr^{-1}.

to changed numbers of flight departures (−31 TJ). The positive energy use gap (46 TJ) for waterborne navigation was mainly due to changes in the vessel types using the prefecture's ports (124 TJ), despite a reduced overall number of vessels having a negative contribution (−78 TJ). Waste incineration's negative energy use gap (−4 TJ) was mainly due to the changed usage rate of combustion agent (−7 TJ), despite the positive contribution owing to increased amounts incinerated (4 TJ). Road transportation's negative energy use gap (−7159 TJ) arose owing to decreased traffic volumes (−7573 TJ) and different types of vehicles (with decreased energy use intensity: −7177 TJ). The negative residential energy use gap (−2334 TJ) was mainly due to a decrease in the total number of households across the seven subregions (−1657 TJ). The negative energy use gap for the industrial and commercial sector (−3608 TJ) was mainly caused by changes to the total number of workers (−7913 TJ), despite a positive contribution from changed energy use intensity (7074 TJ). Agricultural machinery's negative energy use gap (−195 TJ) was mainly due to a decreased total planting area (−166 TJ).

This study used some data with inconsistent spatial or temporal scale, which reduced the accuracy of the analysis results. The spatial resolution of the statistical data limited the characterization of specific details at the level of individual features: e.g., the different energy uses by specific road links/segments and the particular energy use patterns by individual industrial or commercial buildings. Future work will attempt to improve

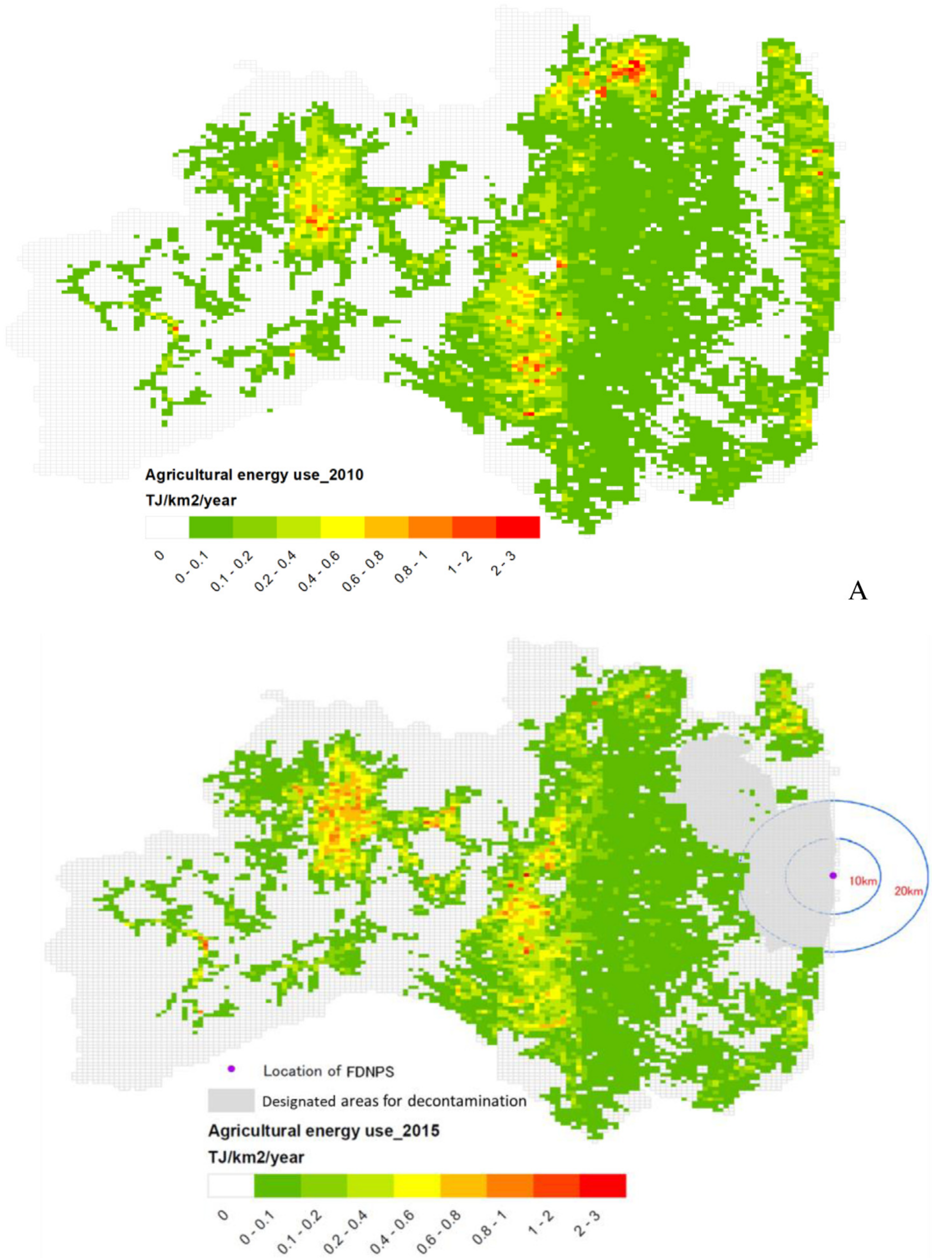

Fig. 11. Energy use by agricultural machines in (A) 2010 and (B) 2015. Unit: TJ km^{-2} yr^{-1}.. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the method's accuracy and spatiotemporal resolution. Future developments include two potential directions. One is to support local government policymaking related to energy use reduction: e.g., prioritizing sectors and factors for controlling when there is great potential for reduction and setting short-term goals for balancing renewable energy developments and reductions in fossil fuel use. Another direction is to broaden the method's applicability by focusing on CO_2 emissions: e.g., validating findings with on-site or satellite observations after inverse processing and developing high-resolution carbon budgets including CO_2 sinks to work toward zero carbon emissions.

CRediT authorship contribution statement

Richao Cong: Conceptualization, Methodology, Formal analysis, Visualization, Validation, Writing – original draft, Revising the draft. **Kei Gomi:** Commentary, Supervision, Project administration, Funding acquisition. **Takuya Togawa:** Formal analysis. **Yujiro Hirano:** Formal analysis, Commentary. **Makoto Oba:** Commentary, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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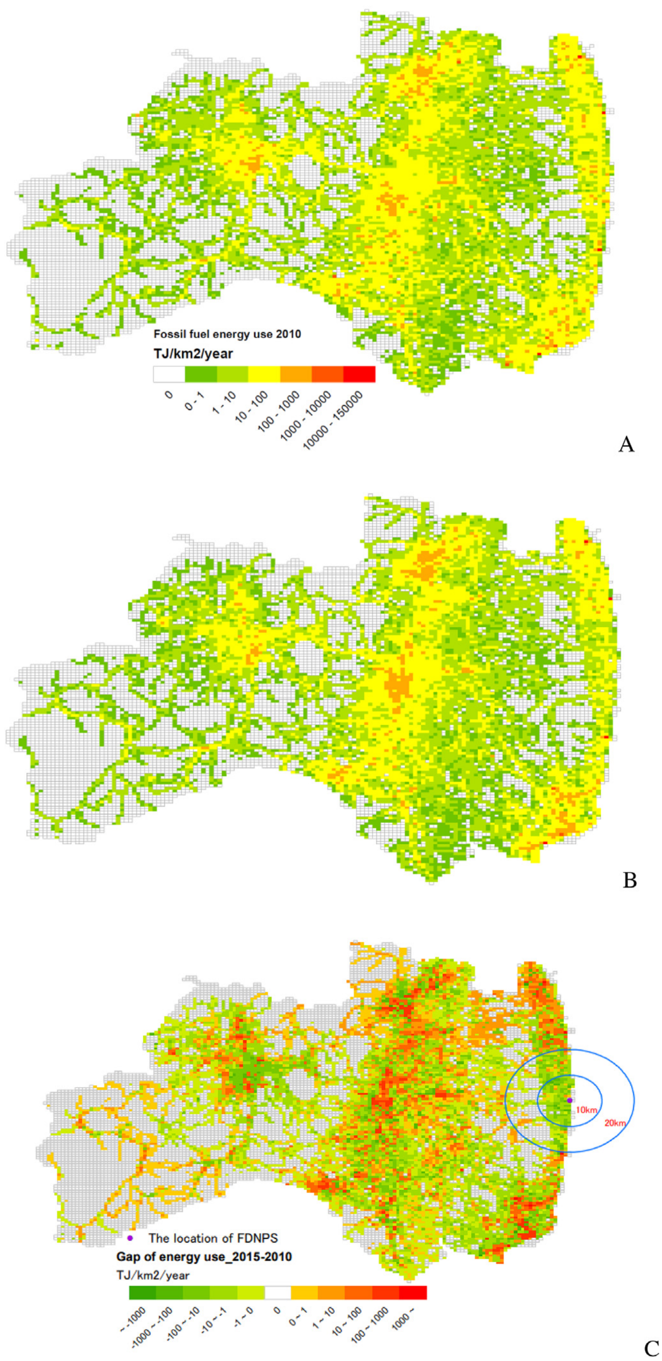

Fig. 12. Energy use by all sectors across Fukushima Prefecture in (A) 2010 and (B) 2015 (same color scale as in (A)). (C) Energy gap between 2015 and 2010. Unit: TJ km^{-2} yr^{-1}.. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.egyr.2021.12.046.

References

Agency for Natural Resources and Energy, 2016a. Statistics Data on Power Plants in 2010 and 2015. https://www.enecho.meti.go.jp/statistics/electric_power/ep002/results_archive.html (Accessed 1 October 2021). (in Japanese).

Agency for Natural Resources and Energy, 2016b. The Description on the Estimation Methods and their Changes in Energy Balance Table. https://www.enecho.meti.go.jp/statistics/energy_consumption/ec002/pdf/ec002_002.pdf. (Accessed 1 October 2021). (in Japanese).

Agency for Natural Resources and Energy, 2017. Energy Balance Table for Fukushima in 2010 and 2015. https://www.enecho.meti.go.jp/statistics/energy_consumption/ec002/results.html#headline2 (Accessed 1 October 2021). (in Japanese).

Agency for Natural Resources and Energy, 2020. Energy White Paper 2020. https://www.enecho.meti.go.jp/about/whitepaper/2020html/2-1-3.html (Accessed 1 October 2021). (in Japanese).

Andres, R.J., Marland, G., Fung, I., Matthews, E., 1996. A 1 × 1 distribution of carbon dioxide emissions from fossil fuel use and cement manufacture, 1950–1990. Glob. Biogeochem. Cycles 10 (3), 419–429. http://dx.doi.org/10.1029/96GB01523.

Aruga, K., 2020. Analyzing the condition of Japanese electricity cost linkages by fossil fuel sources after the Fukushima disaster. Energy Transit. 4, 91–100. http://dx.doi.org/10.1007/s41825-020-00025-y.

Chuah, L.F., Abd Aziz, A.R., Yusup, S., Bokhari, A., Klemeš, J.J., Abdullah, M.Z., 2015. Performance and emission of diesel engine fuelled by waste cooking oil methyl ester derived from palm olein using hydrodynamic cavitation. J. Clean Technol. Environ. Policy 17 (8), 2229–2241. http://dx.doi.org/10.1007/s10098-015-0957-2.

Chuah, L.F., Klemeš, J.J., Yusup, S., Bokhari, A., Akbar, M.M., 2017. A review of cleaner intensification technologies in biodiesel production. J. Cleaner Prod. 146, 181–193. http://dx.doi.org/10.1016/j.jclepro.2016.05.017.

Clean Authority of Tokyo, 2020. Waste Disposal of Tokyo 23cities: Annual Report on the Waste Incineration Plants of Tokyo in 2010 and 2015. https://www.union.tokyo23-seisou.lg.jp/gijutsu/gijutsu/kumiai/shiryo/sagyonenpo.html (Accessed 1 October 2021). (in Japanese).

Cong, R., Gomi, K., 2020. Evidence for the development of energy resilience in fukushima prefecture after the great East Japan earthquake. Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. 44, 37–41. http://dx.doi.org/10.5194/isprs-archives-XLIV-3-W1-2020-37-2020.

Doctor-Heli, 2020. The Monthly Records of the Helicopters in Fukushima Prefecture. https://www.fmu.ac.jp/byoin/DrHeli/index.html (Accessed 1 October 2021). (in Japanese).

Dohi, M., Shinri, S., Masamichi, T., Tomohiro, O., Yoshiharu, N., 2012. Grounds for the calculation of motor vehicle emission factors using environment impact assessment of road project etc. Tech. Note NILIM 671 (8), 1–70, http://www.nilim.go.jp/lab/bcg/siryou/tnn/tnn0671.htm. (Accessed 1 October 2021). (in Japanese).

Eisler, R., 2012. The Fukushima 2011 Disaster. CRC Press, Florida.

Electrical Japan, 2017. Fossil Fuel Fired Power Generation Information. http://agora.ex.nii.ac.jp/earthquake/201103-eastjapan/energy/electrical-japan/area/07.html.ja (Accessed 1 October 2021). (in Japanese).

European Union Aviation Safety Agency, 2017. ICAO Aircraft Engine Emissions Databank. https://www.easa.europa.eu/domains/environment/icao-aircraft-engine-emissions-databank (Accessed 1 October 2021).

Federal Office of Civil Aviation, 2013. Guidance on the Determination of Helicopter Emissions. https://www.bazl.admin.ch/bazl/en/home.html (Accessed 1 October 2021).

Flugzeuginfo.net, 2017. Aircraft Types. http://www.flugzeuginfo.net/acdata_en.php (Accessed 1 October 2021).

Fukushima Prefecture, 2019. The Location, Population, Area of Fukushima Prefecture in 2019. https://www.pref.fukushima.lg.jp/site/ken-no-sugata/ichi-jinko.html (Accessed 1 October 2021).

Fukushima Prefecture, 2020. The Condition of Fukushima Airport in 2010 and 2015. https://www.pref.fukushima.lg.jp/sec/32031b/kuukoudeta.html (Accessed 1 October 2021). (in Japanese).

Gately, C.K., Hutyra, L.R., 2017. Large uncertainties in urban-scale carbon emissions. J. Geophys. Res.: Atmos. 122 (20), 11242–11260. http://dx.doi.org/10.1002/2017JD027359.

Gately, C.K., Hutyra, L.R., Wing, I.S., 2015. Cities, traffic, and CO_2: A multidecadal assessment of trends, drivers, and scaling relationships. Proc. Natl. Acad. Sci. 112 (16), 4999–5004. http://dx.doi.org/10.1073/pnas.1421723112.

Ghosh, T., Elvidge, C.D., Sutton, P.C., Baugh, K.E., Ziskin, D., Tuttle, B.T., 2010. Creating a global grid of distributed fossil fuel CO_2 emissions from nighttime satellite imagery. Energies 3 (12), 1895–1913. http://dx.doi.org/10.3390/en3121895.

Hayashi, M., Hughes, L., 2013. The Fukushima nuclear accident and its effect on global energy security. Energy Policy 59, 102–111. http://dx.doi.org/10.1016/j.enpol.2012.11.046.

Heiple, S., Sailor, D.J., 2008. Using building energy simulation and geospatial modeling techniques to determine high resolution building sector energy use profiles. Energy Build. 40 (8), 1426–1436. http://dx.doi.org/10.1016/j.enbuild.2008.01.005.

Japan Meteorological Agency, 2020. The Database on the Past Climate. http://www.data.jma.go.jp/obd/stats/etrn/index.php (Accessed 1 October 2021). (in Japanese).

Jones, C., Kammen, D.M., 2014. Spatial distribution of US household carbon footprints reveals suburbanization undermines greenhouse gas benefits of urban population density. Environ. Sci. Technol. 48 (2), 895–902. http://dx.doi.org/10.1021/es4034364.

Kharecha, P.A., Sato, M., 2019. Implications of energy and CO_2 emission changes in Japan and Germany after the Fukushima accident. Energy Policy 132, 647–653. http://dx.doi.org/10.1016/j.enpol.2019.05.057.

Kim, Y., Kim, M., Kim, W., 2013. Effect of the Fukushima nuclear disaster on global public acceptance of nuclear energy. Energy Policy 61, 822–828. http://dx.doi.org/10.1016/j.enpol.2013.06.107.

Lerner, J., Matthews, E., Fung, I., 1988. Methane emission from animals: A global high-resolution data base. Glob. Biogeochem. Cycles 2 (2), 139–156. http://dx.doi.org/10.1029/GB002i002p00139.

Min, J., Hausfather, Z., Lin, Q.F., 2010. A high-resolution statistical model of residential energy end use characteristics for the United States. J. Ind. Ecol. 14 (5), 791–807. http://dx.doi.org/10.1111/j.1530-9290.2010.00279.x.

Ministry of Internal Affairs and Communications, 2013. Japan Standard Industrial Classification (Rev. 13, October 2013). https://www.soumu.go.jp/english/dgpp_ss/seido/sangyo/index13.htm (Accessed 1 October 2021). (in Japanese).

Ministry of Land, Infrastructure, Transport and Tourism, 2017. Traffic Census 2010 and 2015. https://www.ktr.mlit.go.jp/road/shihon/index00000005.html (Accessed 1 October 2021). (in Japanese).

Ministry of the Environment, 2017. Investigation Result on the Municipal Solid Waste Disposal Status of Fukushima in 2010 and 2015. https://www.env.go.jp/recycle/waste_tech/ippan/stats.html. (Accessed 1 October 2021). (in Japanese).

Ministry of the Environment, 2018. The Emissions from Ships. https://www.env.go.jp/chemi/prtr/result/todokedegaiH28/syosai/14.pdf (Accessed 1 October 2021). (in Japanese).

Ministry of the Environment, 2020. The Condition of the Contaminated Soil in Fukushima. http://josen.env.go.jp/soil/temporary_place.html (Accessed 1 October 2021).

Morris, B.T., Tran, C., Scora, G., Trivedi, M.M., Barth, M.J., 2012. Real-time video-based traffic measurement and visualization system for energy/emissions. IEEE Trans. Intell. Transp. Syst. 13 (4), 1667–1678. http://dx.doi.org/10.1109/TITS.2012.2208222.

National Institute for Agro-Environmental Sciences, 2003. Life Cycle Assessment for Environmentally Sustainable Agriculture. NIAES Report, http://www.naro.affrc.go.jp/archive/niaes/project/lca/lca_r.pdf. (Accessed 1 October 2021). (in Japanese).

Nelson, J., Johnston, J., Mileva, A., Fripp, M., Hoffman, I., Petros-Good, A., Blanco, C., Kammen, D.M., 2012. High-resolution modeling of the western North American power system demonstrates low-cost and low-carbon futures. Energy Policy 43, 436–447. http://dx.doi.org/10.1016/j.enpol.2012.01.031.

Ocean Policy Research Institute, 2007. Investigation Report on the Environmental Impact of PM by Vessels. http://fields.canpan.info/report/download?id=3269 (Accessed 1 October 2021). (in Japanese).

Oda, T., Maksyutov, S., 2011. A very high-resolution (1 km × 1 km) global fossil fuel CO_2 emission inventory derived using a point source database and satellite observations of nighttime lights. Atmos. Chem. Phys. 11 (2), 543. http://dx.doi.org/10.5194/acp-11-543-2011.

Schneeweiss, S., 2006. Sensitivity analysis and external adjustment for unmeasured confounders in epidemiologic database studies of therapeutics. Pharmacoepidemiol. Drug Saf. 15 (5), 291–303. http://dx.doi.org/10.1002/pds.1200.

Shimizu, N., Yuyama, Y., 2007. Analysis of the energy consumption and profitability of agricultural practice with environmental consciousness-a case study in north-eastern Chiba Prefecture. J. Rural Plan. Assoc. 26, 365–370, https://www.jstage.jst.go.jp/article/arp/26/Special_Issue/26_Special_Issue_365/_article/-char/en (Accessed 1 October 2020). (abstract in English and text in Japanese).

Statistics Japan, 2016. Investigation for Counting the CO_2 Emissions from Households. https://www.e-stat.go.jp/stat-search/files?page=1&toukei=00650408&kikan=00650&result_page=1 (Accessed 1 October 2021). (in Japanese).

Statistics Japan, 2017. Data Download for Population Census, Economic Census, and Agricultural and Forestry Census. https://www.e-stat.go.jp/gis/statmap-search?type=1 (Accessed 1 October 2021). (in Japanese).

Statistics Japan, 2020a. Annual Report on Vessels in Ports. https://www.e-stat.go.jp/stat-search/files?page=1&layout=datalist&toukei=00600280&tstat=000001018967&cycle=7&tclass1val=0 (Accessed 1 October 2021). (in Japanese).

Statistics Japan, 2020b. Statistics Data on New Residential Constructions. https://www.e-stat.go.jp/stat-search/files?page=1&toukei=00600120&tstat=000001016966. (Accessed 1 October 2021). (in Japanese).

Taghizadeh-Hesary, F., Yoshino, N., Rasoulinezhad, E., 2017. Impact of the Fukushima nuclear disaster on the oil-consuming sectors of Japan. J. Comp. Asian Dev. 16 (2), 113–134. http://dx.doi.org/10.1080/15339114.2017.1298457.