Fire Safety Journal 142 (2024) 104025

Contents lists available at ScienceDirect

Fire Safety Journal

journal homepage: www.elsevier.com/locate/firesaf

Spatial-temporal characteristics of more than 50,000 wildfires in Japan from 1995 to 2020

Yoshiya Touge [a,*], Ke Shi [b], Tomoaki Nishino [a], Chenling Sun [a], Ai Sekizawa [c]

[a] Disaster Prevention Research Institute, Kyoto University, Gokasho, Uji, Kyoto, 611-0011, Japan
[b] China Institute of Water Resources and Hydropower Research, Beijing, 100038, China
[c] Center for Fire Science and Technology, Organization for Research Advancement, Research Institute for Science and Technology, Tokyo University of Science, 2641 Yamazaki, Noda, Chiba, 278-8510, Japan

ARTICLE INFO

Keywords:
Wildfires
Fire investigation
Anthropogenic factors
Ignition causes
Water source
Response time
Trend analysis

ABSTRACT

The spatial-temporal characteristics of wildfires were summarized based on fire reports covering 55,863 wildfires with a total burned area of 289.91 km^2 from 1995 to 2020 in Japan. The long-term decreasing trend was largely influenced by changes in social aspects, while the annual fluctuation was determined by large-scale events. The wildfire season started around early January in the southern part and gradually shifted northward over approximately three months. A total of 98.77% of cases were human-induced, and 1.23% were caused by lightning. Regarding response time after receiving the call, firefighting was started within 30 min in 89% of cases and controlled within 1 h in 85% of cases, where spatial characteristics were insignificant. Full-time fire departments utilized artificial water sources primarily in 72% of cases and natural water sources in 28%, while the rate using natural water sources increased as the burned area increased. Natural water sources from ponds and rivers exhibited regionalities. Cluster analysis revealed five wildfire regions reflecting natural and anthropogenic factors. Furthermore, the Mann–Kendall trend test concluded that the initiation process decreased almost uniformly across the country, while regional differences existed regarding the expansion process. Additionally, only human-induced wildfires had a significant decreasing trend.

1. Introduction

Shifts in patterns of wildfire are becoming increasingly important in the context of climate change and the significance of human influence. Several research cases concluded that anthropogenic climate change impacts wildfire regimes in some regions, such as the western United States and Australia [1,2]. Additionally, human influence also has enormous impacts, as human ignition has been one of the primary origins of wildfires [3,4], and protected fire measures can also be dominant, acting as adaptation measures against climate change. The change in wildfire occurrences has been evaluated in many regions worldwide, as well as globally [5,6].

Japan has a humid climate, and wildfires are not as large as those in drier regions of the world. However, more than 1000 wildfires occur annually, and even large-scale events covering an area of several hundred hectares have occurred [7]. Humans play a role in wildfires through ignitions and firefighting services. Natural ignition sources such as lightning occur rarely. Notably, wildfires have spatial-temporal characteristics in Japan. Wildfires mainly occur in spring and have decreased significantly over the last 40 years as a long-term trend [8]. In addition, hydrological conditions greatly differ between the western and eastern sides of the Japanese archipelago. For climate change, the annual mean temperature increased from 0.51 to 2.77 °C on average across all 46 meteorological stations across the country from 1900 to 1996, while changes in precipitation varied by region [9,10]. The social aspect also contain spatial-temporal characteristics. Since human-caused ignitions contribute to the majority of wildfires in Japan [11], a decrease in the number of forestry workers and farmers and a reduction in outdoor recreation could lead to a decrease in the number of ignitions. Although full-time fire departments have been established throughout Japan, the decrease and aging of part-time fire departments have become an issue in recent years [12]. This social change is subject to spatial variation, with conditions greatly differing between urban and rural areas. Both climate and social variations should determine the

* Corresponding author.
E-mail addresses: touge.yoshiya.2z@kyoto-u.ac.jp (Y. Touge), ke.dlut@outlook.com (K. Shi), nishino.tomoaki.3c@kyoto-u.ac.jp (T. Nishino), sun.chenling.27y@st.kyoto-u.ac.jp (C. Sun), sekizawa@rs.tus.ac.jp (A. Sekizawa).

https://doi.org/10.1016/j.firesaf.2023.104025
Received 11 June 2023; Received in revised form 23 August 2023; Accepted 10 October 2023
Available online 11 October 2023
0379-7112/© 2023 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

spatial-temporal characteristics of wildfires.

Fire reports are records of detailed surveys covering all fires since 1995 in Japan consolidated and managed by the Fire and Disaster Management Agency (FDMA). Fire reports include various information, including not only the basic burned area, date and time of initiation but also the ignition and firefighting sources. Reports were compiled for 26 years until 2020, with a total of 55,863 wildfires and 289.91 km^2 of the total burned area. However, to date, there has been no statistical summary of wildfire occurrences in Japan. Therefore, this study summarizes the spatial-temporal characteristics of wildfires obtained from fire reports over the 1995–2020 period. This study aimed to (i) obtain an overview of wildfires in Japan, including social aspects, and (ii) clarify their spatial-temporal characteristics by statistical analysis. The spatial-temporal characteristics of wildfires in Japan are likely to be subjected to both climatic and anthropogenic factors. For example, ignitions and firefighting efforts are likely to be the most significant anthropogenic drivers of wildfire patterns in Japan. This study provides an overview of wildfires in Japan, which have been recorded but never summarized.

2. Materials

2.1. Target area

Japan was chosen as the targeted area of study (Fig. 1). Although the climate can mostly be classified as a humid climate, the hydrological conditions greatly vary within Japan. Since wildfires mainly occur in spring, the climate characteristics during winter and spring are important from this perspective. A mountain range occurs in the central part of the Japanese archipelago, which is bordered by the Sea of Japan and Pacific Ocean. The Sea of Japan side experiences a humid climate in winter, especially in the western Tohoku and northern Chubu regions, which are known for heavy snowfall. Solar radiation is lower in winter than in the other seasons due to cloudy weather conditions. In contrast, the Pacific side is drier, with less precipitation in winter. Moreover, when westerly winds blow over this mountainous area, hot, dry, and strong winds simultaneously occur under the influence of foehn phenomena [13]. After the wildfire season, starting from mid-June, the rainy season begins in the southern part of Japan, but its effects can extend as far as the Tohoku region. However, Hokkaido exhibits no rainy season. Forests occupy 66.3% of the national land area, of which 40.7% includes planted forests and 57.4% comprises privately owned forests [14].

Regarding climatic change, the trend within the targeted period from 1995 to 2020 would not be significant; however, it is becoming an important issue in scoping much longer periods. Statistical analysis by Yue and Hashino (2003a) shows that the temperature increase during 1900–1996 ranged from 0.51 to 2.77 °C at 46 meteorological stations across the country. The average temperature increase from March to May was 1.53 °C on the Sea of Japan side and 1.70 °C on the Pacific side from 1990 to 1996 [9]. Yue and Hashino (2003b) found no statistically significant change in annual precipitation on the Sea of Japan side, while an 11.8% decrease was observed on the Pacific side [10].

The total population has remained almost unchanged since 1995, and population reductions and aging have become increasingly apparent in the countryside. The proportion of the population older than 65 years increased from 14.6% in 1995 to 29.1% in 2020 [15]. The trend of population decline is particularly significant in the Tohoku region, the northern part of the Chubu region, and the Chugoku and Shikoku regions. The number of forestry workers decreased from 81,564 individuals in 1995 to 45,440 individuals in 2015, a 44.3% decrease over 20 years [14]. This has led to an increase in the number of unmanaged forests. Lifestyle also has spatial-temporal characteristics, which will affect fire occurrence. For example, leisure activities in mountainous areas are more common in the spring and fall seasons because the weather conditions are pleasant and wild vegetables can be harvested, while the diversification of leisure activities reduces the number of visitors to mountains in the long term. The smoking population decreased from 52.7% in 1995 to 27.1% in 2019 [16].

Firefighting in Japan is conducted by both full- and part-time fire departments. Regarding full-time fire departments, there are 726 fire department headquarters and 1719 fire stations, and 98.3% of all municipalities exhibit full-time fire departments. There were 166,628 full-time firefighters in 2020 [11]. Part-time fire departments comprise residents with other main jobs who are engaged in disaster management, numbering 818,478 individuals nationwide. Although the number of full-time fire departments has not changed, the decrease and aging of the part-time fire departments are particularly notable in the countryside. The number of members was 975,512 in 1995 and 783,578 in 2022, an annual decrease of 21,299 after 2021. The reduction was larger in the countryside. The age structure is also changing, with 92% of the part-time firefighters under 49 years old in 1993 but 73.8% in 2022. The proportion of forestry and agriculture workers is also decreasing. The proportion of employed firefighters was 64.4% in 1995 and 73.7% in 2019, remaining almost unchanged in the last ten years [12].

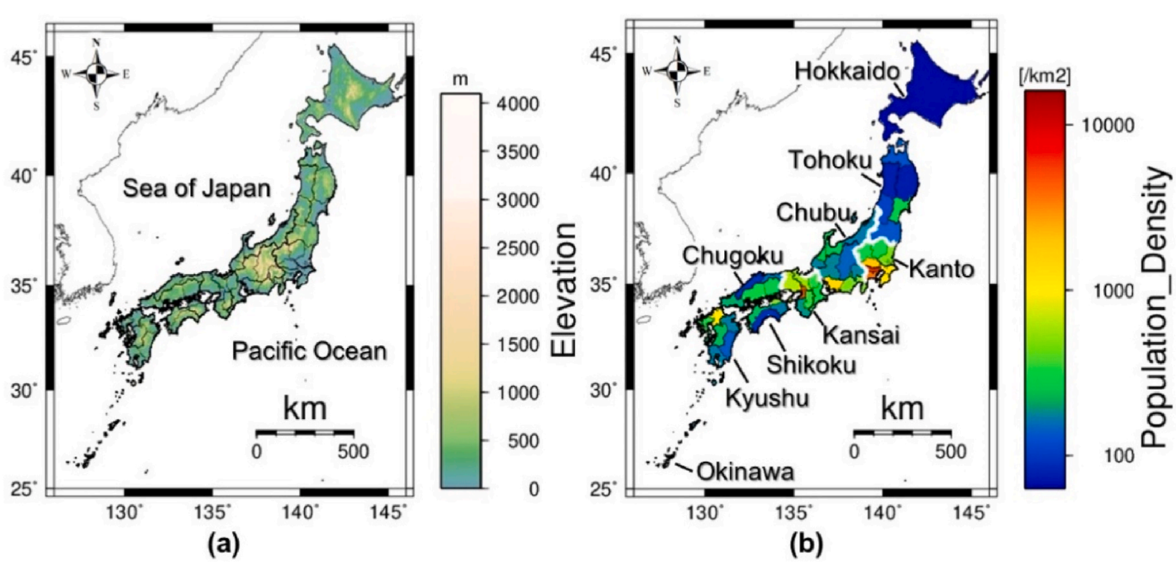

Fig. 1. Topography and population density in Japan. (a) Elevation with the border of prefectures. Elevation data are from the SRTM dataset. (b) Population density of each prefecture. Boundaries of regions are drawn in white.

2.2. Fire reports

Fire reports contain Japanese fire investigation data compiled since 1995, when the FDMA began to consolidate data after fires using a uniform nationwide postfire investigation method. The purpose of investigating these data reports is to accurately identify the causes, damage, and characteristics of fires and to implement effective fire prevention measures. Surveys were conducted according to the Handbook of Fire Statistics [17]. A fire is defined as a combustion phenomenon that is unintentionally started or caused by arson and requires the use of fire extinguishing equipment or equally effective means. A single fire is defined as one that has spread from a single point of origin, beginning with fire initiation and continuing until extinguishment. The investigation covers all fire phenomena occurring in the territory of Japan.

The survey items used in this study are listed in Table 1. The prefecture and city indicate the location of fire initiation (Table entry 1a). Fire types can be classified as building fires, wildfires, vehicle fires, vessel fires, aircraft fires, and other fires (Table entry 1b). However, only wildfires are considered in this study. A wildfire is defined as a fire during which forests, wilderness, and pastures are destroyed. When multiple types of fires simultaneously occur, the type resulting in the highest economic loss is selected. The date and time at which the call was received indicate when the fire department became aware of a given fire (Table entry 1c). The date and time at which firefighting commenced indicate the moment when firefighters started spraying water at the scene (Table entry 1d). If no water was discharged, the corresponding field was left blank. The date and time at which the fire was controlled indicate the moment when the fire was brought under the control of the firefighters, as certified by the highest commander at the scene (Table entry 1e). If no water spraying occurred, this field was left blank. The water source primarily used for firefighting was independently recorded for full- and part-time fire departments (Table entry 1f). The causes of the fire (Table entries 1 g-i) include the ignition source, ignition sequence, and first fuel ignited. The burned area was calculated by the horizontal projected area (Table entry 1j).

Importantly, these fire reports contain personal and private information. Therefore, all fire information presented in this study was averaged, summed, and statistically processed, and any information on individual cases not publicly disclosed was not included.

On March 11, 2011, the Great East Japan Earthquake occurred. The resulting tsunami caused numerous fires, including large-scale wildfires. However, since this study focuses on long-term changes in climate and anthropogenic influences, 155 wildfire cases that occurred during the 10-day period after March 11, 2011 were excluded from the calculation process. Not all cases should have been caused by the earthquake but were removed because the causes could not be determined.

2.3. Statistical analysis

This study first presents a summary of wildfires in Japan based mainly on the average of long-term data, while cluster analysis and trend analysis are presented afterward.

Table 1
Utilized elements from fire reports.

	Element		Element
(a)	Prefecture and city	(f)	Water source primarily used for firefighting
(b)	Type of fire	(g)	Ignition source
(c)	Date and time at which the call was received	(h)	Ignition sequence
(d)	Date and time at which firefighting was started	(i)	First fuel ignited
(e)	Date and time at which the fire was controlled	(j)	Burned area

Regarding cluster analysis, the Mclust toolkit version 6.0.0 (Scrucca et al., 2016) was used within the R statistical programming language version 4.2.2. This process comprises three elements: (1) initialization via model-based hierarchical agglomerative clustering; (2) maximum likelihood estimation via the expectation–maximization (EM) algorithm [18]; and (3) selection of the Bayesian model and a number of clusters using approximate Bayes factors with a Bayesian information criterion approximation [19]. The Mclust toolkit can solve three key problems: the number of clusters, the clustering method to be adopted, and the management of outliers.

To detect trends in the long-term time series of wildfires, a trend-free prewhitening Mann–Kendall (TFPW-MK) test was performed [20]. The Mann–Kendall (MK) test is often applied in trend analysis [21]. However, this method requires independent time series, while time series data often exhibit serial correlations. The TFPW-MK test method is a modified version of the MK test method that eliminates serial correlation effects. In the trend analysis, all items were annually averaged and used for calculation.

3. Results

3.1. Long-term average of fire occurrences

Table 2 provides the total data for the 26-year study period. On average, more than 2000 times/year and more than 11 km^2/year were burned by fire. In comparison, there were 21,003 building fires and 3585 vehicle fires in 2019 [11]. In Japan, a humid area, the size of individual wildfires was small, with each fire destroying less than 1 ha of land, but the average area destroyed by the top 10% of the largest fires exceeded 4 km^2/year.

3.2. Long-term change and temporal characteristics

Fig. 2 shows the temporal characteristics. This section discusses the characteristics of wildfires by dividing them into the processes of fire initiation and fire spread. The former is when a fire starts from natural or human-caused ignition, grows to an uncontrollable scale, and is expressed by the number of fires. The latter indicates the ease of fire spread after initiation and is expressed by the burned area per fire as well as the burned area per year [8]. Both vary by region and time, and are influenced by natural conditions such as dryness, strong winds, fuel, and social factors such as ignition and firefighting activities.

Fig. 2a shows values by year, and Fig. 2b shows values by fire. As previously reported [8], the number of wildfires and the burned area rapidly decreased until approximately 2003, after which the reduction slowed, and finally reduced to 30–40% of the 1990s level. Despite the observed decline, there were still more than 1000 fires per year. Although the total number of fires per year decreased, the burned area per fire and that for the top 10% of the largest cases did not significantly change. This indicates that the fire initiation process is more important than the fire spread process in the past long-term reduction. On the other hand, the burned area per fire had a large annual variation, and the values for all events and the top 10% of the largest cases showed similar trends. Additionally, Fig. 2c shows the total burned area for the top 10%, 30%, 50%, and 100% of the largest fires each year. The top 10% of the largest cases accounted for approximately 90% of the total burned area each year, and this ratio did not significantly change. Therefore, the area

Table 2
Long-term average annual values from 1995 to 2020.

Element	Unit	Value
Number of fires per year	–	2149
Burned area per year	ha	1115
Burned area per fire	ha	0.52
Burned area per fire for the top 10% of the largest events	ha	4.66

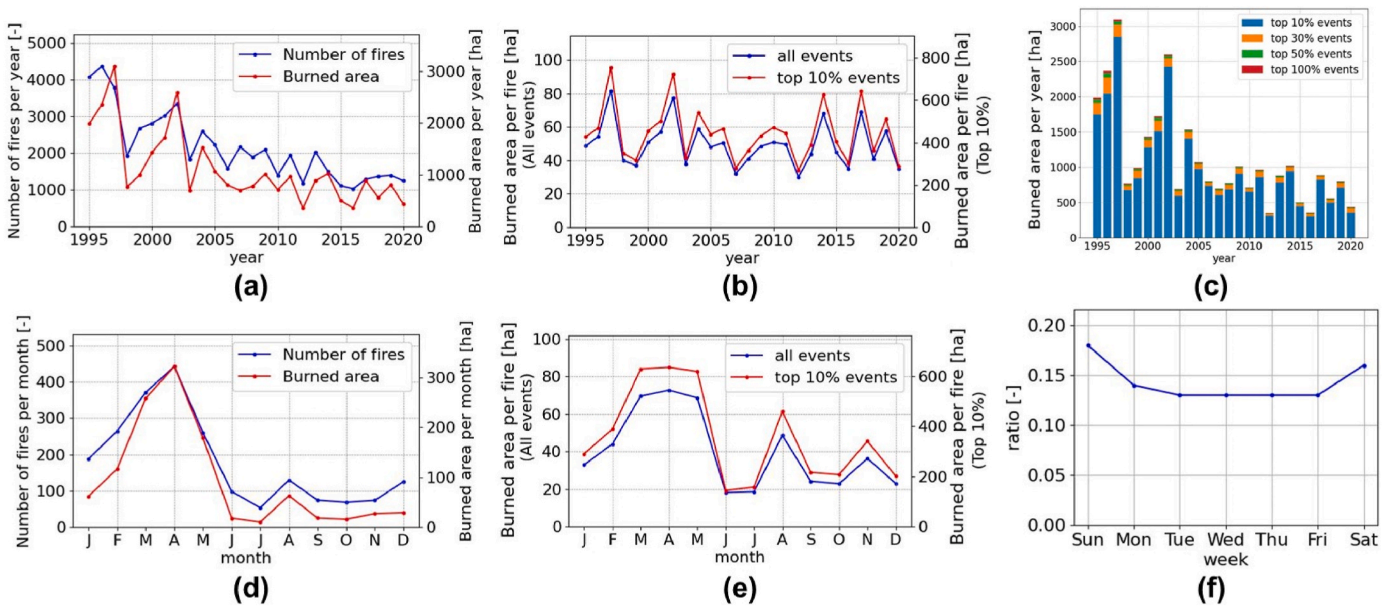

Fig. 2. Temporal characteristics of wildfire in Japan. (a) The total number of wildfires and burned area per year. (b) Annual burned area per fire for all events and the top 10% of the largest events. (c) Burned area per year with a ratio of top events. (d) The total number of wildfires and burned area per month. (e) Monthly burned area per fire for all events and the top 10% of the largest events. (f) The ratio of the number of fires each day in the week.

per case is determined by a small number of large-scale fire cases rather than by the uniform change in the size of all fires. Therefore, it is necessary to consider the factors of large-scale wildfires when focusing on the annual fluctuation in the area burned. Since the influence of climate change should be limited during only 26 years from 1995 to 2020, the long-term reduction to approximately 30% would be due to the influence of social changes. However, since the annual variation in the burned area per fire was determined by large-scale events, it is also important to understand natural factors, such as extreme dryness and strong winds. Similar to Japan, significant reductions have been

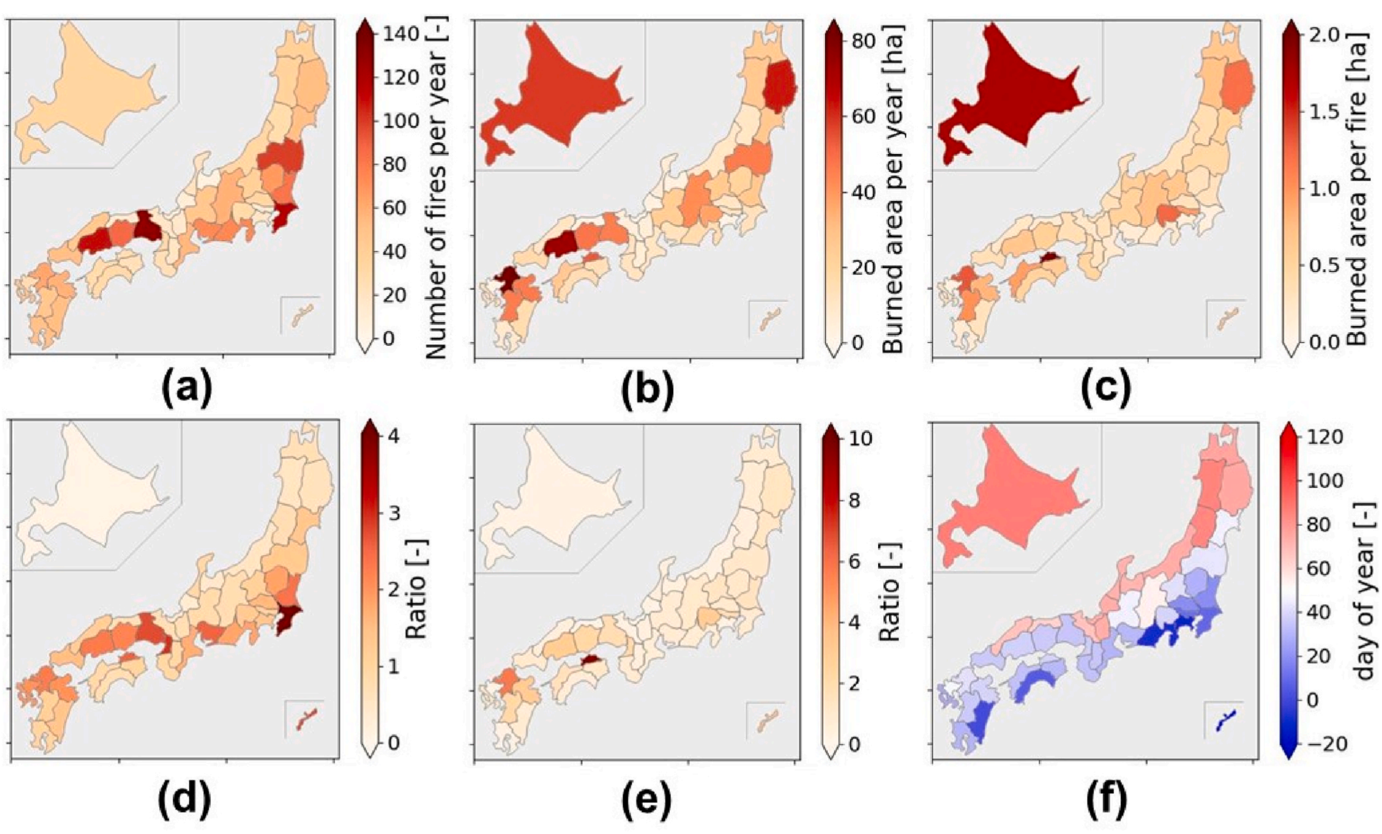

Fig. 3. Spatial characteristics of wildfire in Japan. (a) Number of fires per year. (b) Burned area per year. (c) Burned area per fire (d) The national average rate of the number of fires divided by the prefecture's area. (e) The national average rate of the burned area divided by the prefecture's area. (f) Starting date of the fire season based on the number of fires. In the figure, Hokkaido is shown on the upper left, and Okinawa is shown on the lower right.

reported or projected in some regions by global studies [21,22]. For example, in the case of China, both the number of fires and burned area per fire decreased significantly from the 2000s [4].

Fig. 2d and e shows monthly averages. Wildfires in Japan exhibit notable seasonal influences, mainly during the spring, from the winter to the prerainy season. The burned area per fire in Fig. 2e also exhibits clear seasonal changes, and its temporal characteristics were determined by the top 10% largest cases, similar to the annual variation in long-term changes. Fig. 2f is another temporal characteristic, showing the number of fires ratio by day of the week. Here, seasonal changes were influenced by both natural and anthropogenic conditions, such as the increase in visitors for recreational purposes, while daily variations in a week should be determined only by anthropogenic conditions. The seasonal variation in Fig. 2d and e is 5~10 times, comparing the highest and lowest, where natural conditions would be more significant. Notably, fire initiation was more affected than fire spread in Fig. 2d and e. This is because natural conditions influencing fire initiation are mostly related to seasonally changing natural factors, while other factors, such as wind speed, also affect the fire spread process significantly.

3.3. Spatial characteristics of wildfire occurrence

Fig. 3 shows the spatial variation in wildfire occurrences by prefecture. Fig. 3a shows that the number of fires tended to be large on the Pacific side of the mountain range. In particular, there are more than 100 wildfires per year in some prefectures surrounding the southern Chugoku region and the southern Kanto region. The Chugoku region is a drought-prone region, such as water scarcity, where the annual precipitation in this region is 1000~1600 mm/yr, which is lower than the national average of 1700~1800 mm/yr [10,23]. In contrast, the northern part of the Kinki and Chubu regions exhibited fewer cases than the other regions, with approximately 10 cases/year. The spatial distribution of the burned area in Fig. 3b also has similar spatial characteristics. Comparing the number of fires, regions such as Hokkaido, eastern Tohoku, and northern Kyushu were high. However, although the number of fires was high in the Kanto region, the burned area was smaller. In addition, Fig. 3c shows the burned area per fire. That was remarkably high in northern Shikoku and Hokkaido, followed by eastern Tohoku and northern Kyushu. Since the number of fires and the total area of fires shown in Fig. 3a and b, respectively, depend on the prefecture area, Fig. 3d and e can be obtained by dividing Fig. 3a and b, respectively, by the prefecture area. To clearly reveal the spatial variation, the national average rate was determined. It was observed that the number of fires was larger in the area from northern Kyushu to the Kanto region. These are the most densely populated areas in Japan and are located on the Pacific Ocean side of the Japanese archipelago, which is dry in winter [10,23].

Fig. 3f shows the starting date of the fire season. In this research, the fire season was defined as the period comprising 90 consecutive days with the largest number of wildfires. This definition was made because the FDMA operates to alert the fire for three months from March to May as the fire susceptibility season [11]. The fire season starts around early January in the southern part and gradually moves northward over approximately three months, starting around late March in the western Tohoku region and Hokkaido. The shift in the wildfire season would be determined by dryness and vegetation. In addition, the heavy snowfall occurring in the northern part of Japan could explain the smaller number of wildfires in winter than during the other seasons due to the occurrence of snow-covered surfaces. Okinawa is unique, which is the southernmost prefecture in Japan, where the wildfire season starts at the end of October. Since the definition of fire season is 90 consecutive days with the largest number of wildfires, sufficient data for determining the period cannot be obtained from a single year. Therefore, this research did not show long-term changes in the fire season, although it is also an important subject in climate change [6,24]. Jolly et al. (2015) showed that there was almost no change in the wildfire season in Japan from 1979 to 2013 during the global analysis [24], but local data should confirm this result. Furthermore, since the hydrological factors that contribute to the occurrence of wildfires vary in region, it is difficult to determine the dominant factors for the occurrence of wildfires. Future research is needed to identify regional and seasonal drying factors and their shifts to examine their spatial characteristics.

3.4. Wildfire cause

Fig. 4 shows the fire occurrence by the ignition source and the first fuel ignited. Firebrand refers to the burning of flying objects resulting from other burning sources, such as bonfires and incinerators. As shown in Fig. 4a, regarding the percentage of ignition sources excluding unknown cases, 98.77% of wildfires in Japan were human-induced, such as bonfires (35.54%), cigarette-related fires (26.54%), and open burning-related events (15.16%). Lightning accounted for only 1.23% of the total number of fires, which comprises the largest proportion of natural ignition sources. As described in section 3.2, hydrological conditions significantly affect fire initiation, while most fires in Japan are caused by human ignition. This indicates that both anthropogenic and hydrological influences are significant in wildfires in Japan. In the case of China, human-caused fire accounted for 95.7%, and 4.3% was lightning-caused [4]. Naturally triggered cases were similarly rare but even lower in Japan.

As shown in Fig. 4b, most of the first fuel ignited is related to dead plants, such as dead grass (58.44%) and defoliation (30.13%), with only 2.94% of the total sources attributable to living trees, where unknown cases were excluded. This result indicated that standing trees are not easily burned in Japan. Generally, since fire intensity in Japan is not high, most wildfires are surface fires and rarely lead to crown fires [7]. Regarding their long-term changes, all of the main items indicated a decreasing trend. These decreasing trends were compared among the factors in later trend analysis. Fire reports also record the ignition sequence leading up to the fire. Malicious causes of arson accounted for 10.91% of the total number of causes, and negligence, such as fire mismanagement, explained most of the other fires.

3.5. Required time for firefighting

The time for firefighting was divided into three categories: the time to start firefighting from receiving the call (time 1), the time to control the fire from the start of firefighting (time 2), and the time to control the fire from receiving the call (time 3). These were firefighting processes, including preparation. The fire report also provides the time to extinguish the fire, which the highest commander decides, but it was not considered in this section. That is because it is highly affected by the individual situation, and controlling fire would be the most important for firefighting.

First, since there were cases where the recorded values contained errors, the following cases were removed from the data under conditions (a) through (e). The conditions for exclusion were as follows: (a) cases where the required time was not available or zero, (b) cases where time 1 or time 3 exceeded 60 days, (c) cases where time 1 exceeded 48 h, (d) cases where the burned area was smaller than 1 ha and time 3 was longer than 72 h, and (e) cases when the burned area was smaller than 10 ha and time 3 was longer than 28 days. A total of 181 cases of wildfires were excluded. Although some events with correct values were removed in this process, it would be more appropriate to discuss the data on a reliable normal scale rather than to discuss extreme cases with the possibility of including error values.

Fig. 5a shows the required time for firefighting as a rate of cases non-exceeding the time. Firefighting started in 23% and 89% of cases within 10 and 30 min after receiving the call (time 1), whereas 48% and 81% of wildfires were controlled within 10 and 30 min after starting firefighting (time 2). In total, 60% and 85% of wildfires were controlled within half and 1 h after receiving the call, respectively (time 3). The FDMA hasn't

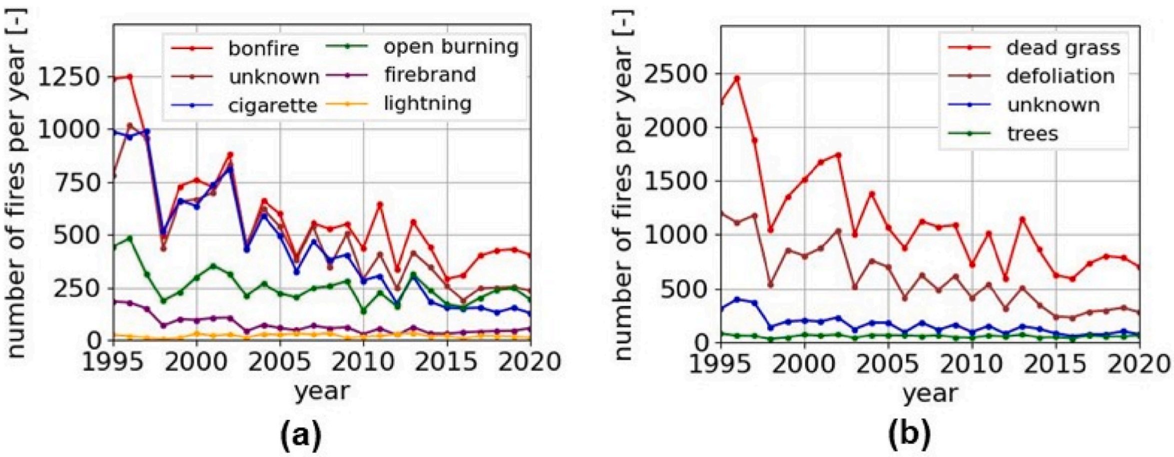

Fig. 4. Ignition sources and the first fuels ignited wildfires in Japan. (a) Changes in each ignition source. (b) Changes in each first fuel ignited.

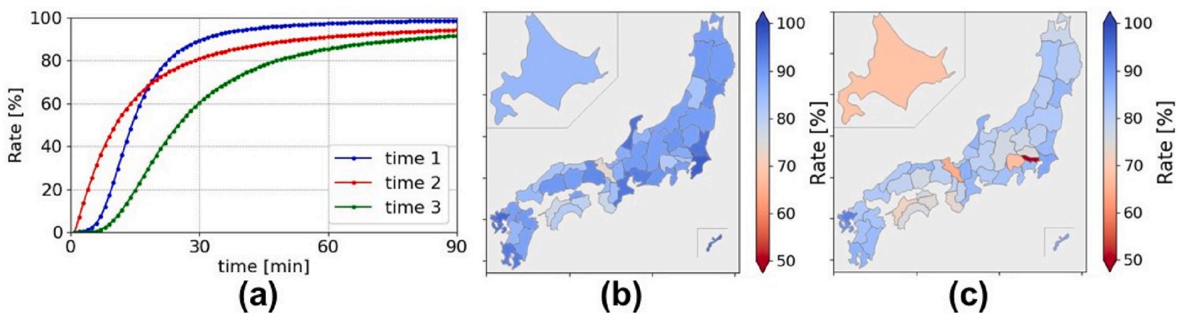

Fig. 5. Required time for firefighting in Japan. (a) The required time for each firefighting process as a rate of cases non-exceeding the time. (b–c) Rate of cases longer than 30 min for each firefighting process, where (b) starts firefighting from receiving the call (time 1) and (c) controls the fire from the start of firefighting (time 2).

established a designed standard time for wildfires, but in the case of fires in cities, it is 6.5 min or less for time to start the firefighting from the time to leave fire stations, which includes 4.5 min for arrival and 2 min for preparing water discharge after arrival. However, the point where wildfires start is farther from the base, so more time is required. Fig. 5b and c shows the rate of the cases within 30 min at time 1 and time 2, respectively. The results showed regional differences. Time 1 does not show a significant spatial difference, but the Shikoku region and some parts of Kinki have lower values. Time 2 had more regionality; it was low in Hokkaido, some in the Kinki region, and the lowest in Tokyo in the Kanto region. The low in Tokyo would be because the decisions on fire control were made carefully, particularly in the urbanized areas. In several research cases, 30 min was set as the critical response time for initial firefighting for fast-spreading fires [25,26]. Therefore, firefighting started within 30 min in 89% of cases, and the rate was uniformly high in Japan, indicating high firefighting capability in Japan. For further research, understanding the difference in response time is needed, which can also be attributed to high population density, road network, and slower fire spread speed due to the humid climate.

3.6. Water source for firefighting

In general, water use for firefighting can be classified into artificial and natural water sources. The former includes fire engines, fire hydrants, and tanks; the latter includes rivers, ponds, oceans, and lakes. Artificial water sources are planned based on the standards of water sources for firefighting of the FDMA. Therefore, these sources are widely prepared and well used in many fire cases. The standard water amount is a water storage of 40 m^3 or a continuous water supply of 1 m^3/min for 40 min. However, it is difficult to establish a high-density artificial water supply in forested areas due to the vast area of the targets. Therefore, the FDMA emphasizes development in regions near residential areas due to concerns regarding the wildland urban interface (WUI). In contrast, natural water sources can provide water for long periods and in large quantities. In general, even small rivers can provide a flow rate of 1 m^3/s or more, which is well above the 1 m^3/min value mentioned above. For example, in Kagawa Prefecture in the northern Shikoku region, the average water storage of a single pond could reach 11,000 m^3. In areas with no water available for firefighting, the water tank of fire engines is used. In most cases, the water storage capacity of the tank is 1.5–5 m^3 per vehicle.

Fig. 6 shows the number of wildfire cases with the frequently used water sources primarily used for firefighting, expressed as a percentage. Fig. 6a shows the frequency of water sources for full-time fire departments, and Fig. 6b shows those for part-time fire departments. Artificial water sources provide 72% of the water sources for full-time fire departments, but the proportion of natural water sources increased with increasing burned area. In the large-scale cases of more than 100 ha, the frequency of natural water sources was 52% vs. 40% for artificial water sources. Part-time fire departments generally do not own fire engines with water tanks, so the proportion of natural water sources was high for all fire cases (regardless of the size). Water withdrawal from rivers did not significantly change regardless of the burned area, but the use of ponds was higher in large-scale cases.

Fig. 6c–f shows the distribution of sources by prefecture for full-time fire departments. In many prefectures, the frequency of fire engine water tanks exceeded 40%. However, in the Chugoku and Shikoku regions, the share ranged from 10 to 30%, and the use of fire hydrants was high. However, the utilization frequency of rivers and ponds were highly regional, where river water tends to be utilized on the Sea of Japan side

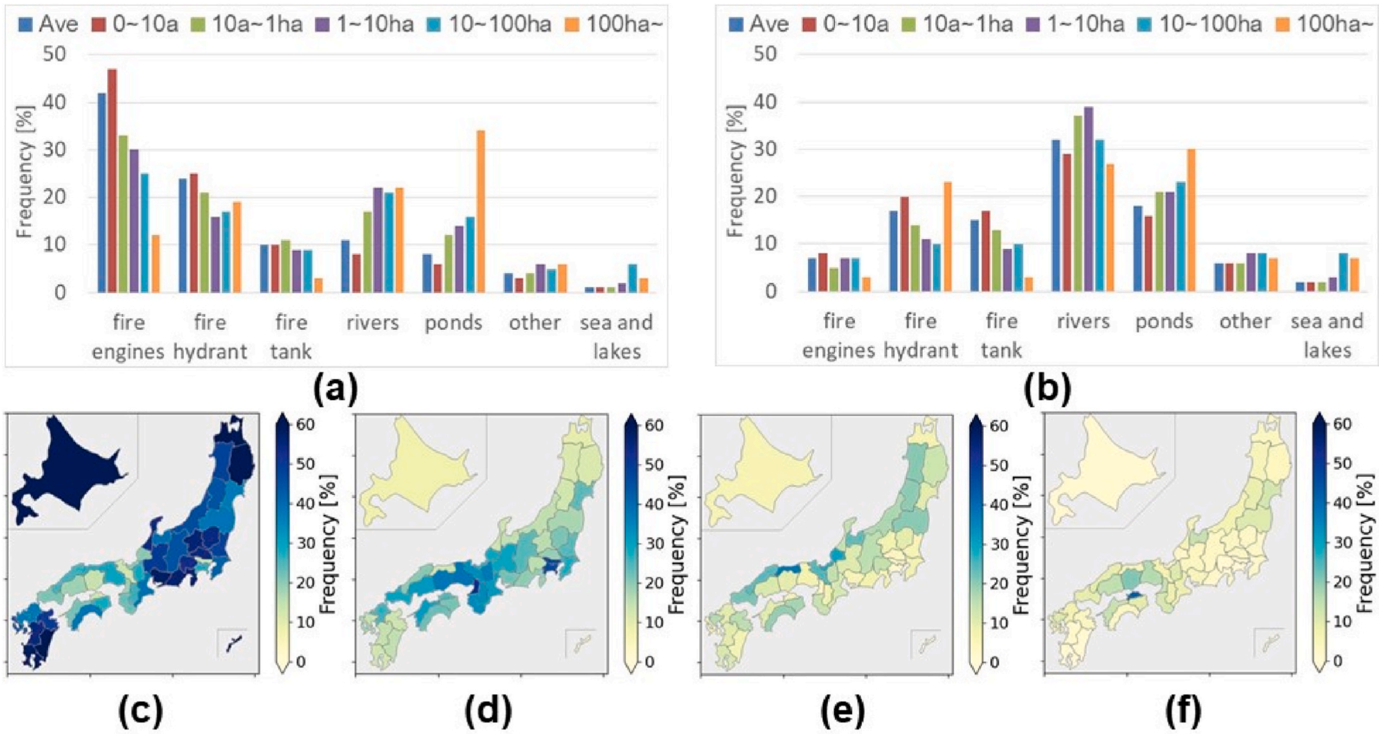

Fig. 6. Water source primarily used for firefighting. (a) Frequency of water source for the full-time fire department. (b) Frequency of water source for the part-time fire department. (c–f) Frequency of primarily used water sources from all wildfire events by full-time fire departments, where (c) fire engines, (d) fire hydrants, (e) rivers, and (f) ponds.

and ponds for the Chugoku and Shikoku regions. This area surrounding the Chugoku and Shikoku regions is historically known to contain many ponds for agricultural use because of its susceptibility to drought. The ten prefectures surrounding the Chugoku, Shikoku, and western Kinki regions account for 52.3% of the total number of ponds in Japan (152,151 ponds). The frequency in Kagawa Prefecture, located in northern Shikoku, exceeds 30%, and it exhibits the highest density of ponds per prefecture area [27]. However, the maintenance and management of agricultural ponds are becoming difficult because of population reduction [28]; thus, it is necessary to pay attention to natural water sources for firefighting as one of the social factors.

4. Statistical analysis

4.1. Cluster analysis for wildfire region map generation

The results of the previous chapters indicated spatial-temporal characteristics depending on climatic and social conditions. In this section, we generate regional wildfire classification maps by classifying the characteristics of fire occurrence based on a general statistical approach [21]. Mapping of regional classification is effective for integrating data with similar trends and for analyzing data in regions with limited available data, and has been used in many research cases [5,21]. Cluster analysis was conducted using fire occurrence by prefecture as input. The inputs for cluster analysis were as follows: (a) the number of fires per year divided by the prefecture area [/km^2], (b) the burned area per year divided by the prefecture area [ha/km^2], (c) the burned area per fire [a], and (d) the starting date of the fire season based on the number of fires [day]. Fig. 7 shows the cluster map.

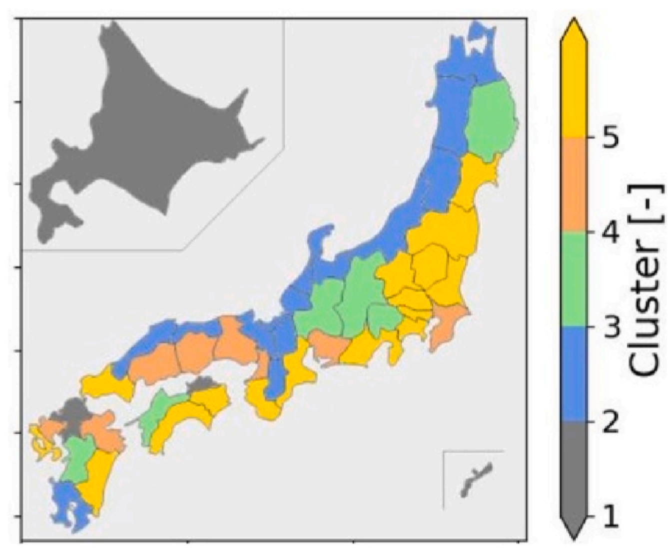

Fig. 7. Cluster map of wildfires in Japan.

Cluster 1 would be the unique prefectures that were difficult to classify. Cluster 2 encompasses the Sea of Japan side of the mountain range, characterized by a humid winter with heavy snowfall, especially in the northern region. The number of wildfires in this cluster is smaller, and the start of the fire season is later than that in the other clusters, as shown in Fig. 3f. Cluster 3 is an even less populated area that not only includes mountainous areas but also includes a large forested area, with a large average burned area per fire, as shown in Fig. 3c. Clusters 4 and 5 are located on the Pacific Ocean side and experience dry weather from winter to spring. Cluster 4 is a highly populated area with many fires and burned areas. Cluster 5 includes areas where the number of fires and the burned area are smaller than those in Cluster 4. The classification dividing the Japanese archipelago into east–west regions is due to the large differences in climatic conditions, and is consistent with other studies showing different characteristics [23,29]. In addition to the natural factor of the mountain range side, the large number of fires around densely populated areas, as shown in Fig. 3d and e, is reflected in the classification. Clusters 3 and 5 were widely distributed in a north–south direction, which differs from the other classification cases that reflect only natural conditions [23,29]. The classification of wildfires was based on both natural and anthropogenic factors.

4.2. Long-term trend analysis

The various spatial-temporal characteristics in section 3 included on the time series of changes; in this section, the increasing and decreasing trends were quantified by the Mann–Kendall trend test [5,21]. The intention is as follows: time series with different absolute values can be compared, and temporal characteristics can be compared in spatially distributed map.

Fig. 8 shows the trend analysis results. Fig. 8a–c shows the long-term change in the national average, and Fig. 8d–g shows the results by prefecture. Fig. 8a shows a significant downward trend in the number of fires and burned areas, with a more notable downward trend in the number of fires. In contrast, the burned area per fire exhibited relatively lower decreasing trends. In Fig. 8d–g, the number of fires indicated a significant downward trend almost uniformly in most regions, while trends in the burned areas showed more variety. These figures suggest that while the ignition process has decreased almost uniformly across the country due to human influence, regional differences exist in how the burned area has subsequently expanded. In prefectures with large forested areas, there is an increase in the area of individual fires, which large cases should influence. Therefore, it is necessary to pay attention to the changes in the overall trend of initiation caused by human influence and the changes in the large-scale cases enhanced by natural conditions. In terms of the expansion process, since there was no significant spatial difference in time for firefighting, the contributions of hydrometeorological conditions would be more dominant.

Fig. 8b shows the trend by ignition source. Many sources revealed a decreasing trend, with the largest decrease in cigarettes, probably due to the decrease in the smoking population. In contrast, the only natural ignition source, lightning, remains almost unchanged. Here, considering the decreasing trend in the number of fires depicted in Fig. 2a, the decreasing trends of all ignition sources could be consistent if drastic changes occurred because of climate change. However, the decreasing trend of lightning-caused fires differed from that of fires attributable to other anthropogenic factors. Therefore, the decreasing trend in the number of fires, as shown in Fig. 2a, is largely due to anthropogenic factors. In the case of California, anthropogenic ignition sources also had decreasing trends, such as arson and smoking, while lightning had some long-term changes for approximately 100 years until 2016 [30].

No significant change was observed for the water sources primarily used for firefighting, as shown in Fig. 8c. This trend analysis result was expected since the maintenance of each water source could differ, particularly natural water sources in the countryside. However, the difference among the various water sources was small.

5. Conclusion

The spatial-temporal characteristics of wildfires in Japan were summarized, and the natural and social conditions underlying wildfires were demonstrated. The results revealed the following conclusions.

(i) Long-term decreasing trends and annual fluctuations were observed in the number of fires and burned area. The long-term decreasing trend was largely influenced by the decrease in the number of human-caused fires, while the annual fluctuation was determined by large-scale events. In contrast, the trend of burned area per fire was insignificant, as well as the top 10% of the largest cases. A total of 98.77% of wildfires were human-induced, and 1.23% were caused by lightning, in which only anthropogenic factors showed a significant downward trend.

(ii) The distribution by prefecture indicated a large difference between the Sea of Japan and the Pacific sides of the mountain range. Many fires tend to occur near densely populated areas. The wildfire season starts around early January in the southern part and gradually moves northward over approximately three months. Cluster analysis revealed five wildfire regions reflecting such natural and anthropogenic factors.

(iii) The full-time fire department utilized artificial water sources in 72% of all wildfire cases because they were widely prepared in Japan. In contrast, natural water sources were utilized in 28% of

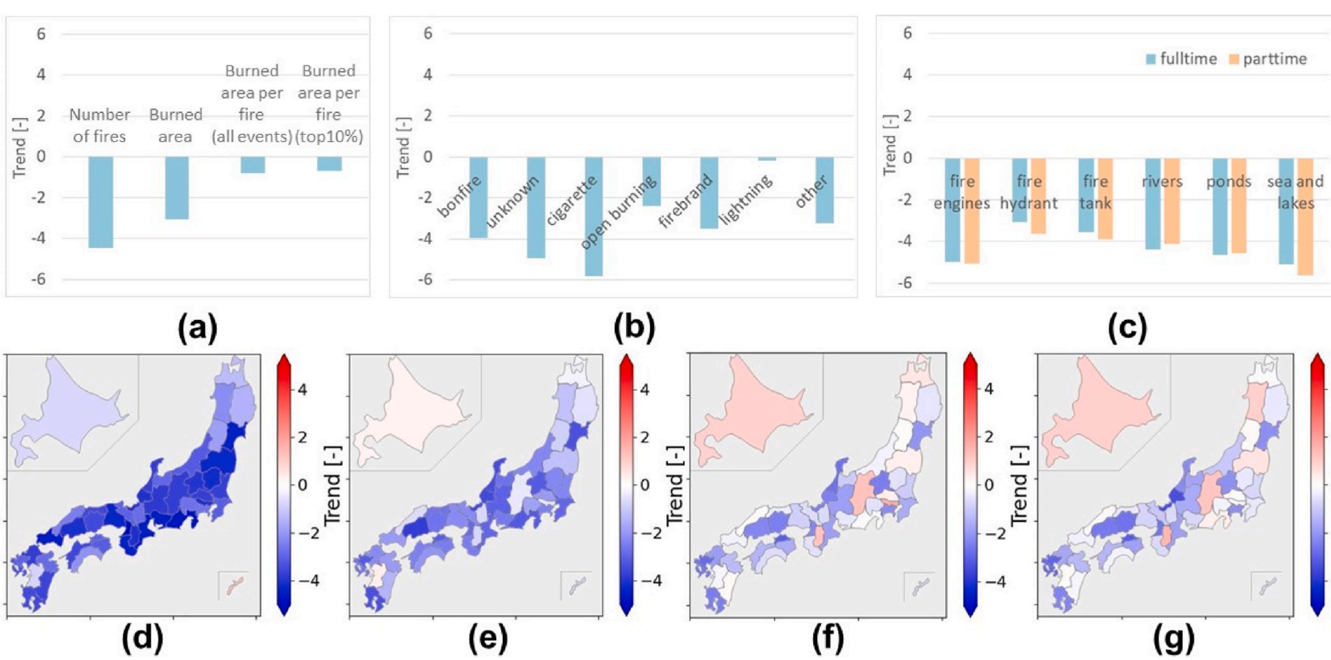

Fig. 8. Trends of wildfire and firefighting in Japan. (a) Trends for fire occurrence. (b) Trends in each ignition source. (c) Trends in each water source primarily used for firefighting. (d) Trends in the number of fire occurrences. (e) Trends in burned areas. (f) Trends in burned area per fire (all events). (g) Trends in burned area per fire (only top 10% events).

cases, and the rate increased as the burned area increased. In addition, natural water sources from rivers and ponds indicated a significant level of regionality.

(iv) 85% of wildfires were controlled within 1 h after receiving the call. 89% of cases started firefighting within 30 min after receiving the call, while 81% of cases were controlled within 30 min after starting firefighting. Slight regional variations were observed; however, they were not significant. Although the decline in the number of part-time firefighters has become a problem in rural areas, the required time is still uniformly short in Japan.

(v) The Mann–Kendall trend test concluded that the initiation process decreased almost uniformly across the country, while regional differences existed in how the burned area subsequently expanded. Therefore, the change in the initiation process caused by social change and the expansion process in large-scale cases enhanced by natural conditions, are important to consider. Notably, a change in firefighting would not influence the spatial difference in the expansion process since its regionality was not significant in time for firefighting.

Although this research aims to show spatial-temporal characteristics, it did not demonstrate quantitative reasoning. For example, the factors that cause wildfires vary in regions due to the diversity of climatic and anthropogenic factors that affect them, as many of these factors are difficult to quantify. In addition, while some of the results are influenced by large-scale cases, the factors are also diverse and require detailed investigation case-by-case. Therefore, future research should attempt to explain the obtained results of spatial-temporal characteristics by various factors.

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.

Data availability

The authors do not have permission to share data.

Acknowledgments

This work was conducted by Theme 4 of the Advanced Studies of Climate Change Projection (SENTAN Program) Grant Number JPMXD0722678534, Grant-in-Aid for Scientific Research (B), 2020–2023 (20H02248; Yoshiya Touge) supported by the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan.

References

[1] J.T. Abatzoglou, A.P. Williams, Impact of anthropogenic climate change on wildfire across western US forests, Proc. Natl. Acad. Sci. USA 113 (2016) 11770–11775, https://doi.org/10.1073/pnas.1607171113.

[2] N.J. Abram, B.J. Henley, A. Sen Gupta, T.J.R. Lippmann, H. Clarke, A.J. Dowdy, J. J. Sharples, R.H. Nolan, T. Zhang, M.J. Wooster, J.B. Wurtzel, K.J. Meissner, A. J. Pitman, A.M. Ukkola, B.P. Murphy, N.J. Tapper, M.M. Boer, Connections of climate change and variability to large and extreme forest fires in southeast Australia, Commun, Earth Environ. 2 (2021) 8, https://doi.org/10.1038/s43247-020-00065-8.

[3] J.K. Balch, B.A. Bradley, J.T. Abatzoglou, R. Chelsea Nagy, E.J. Fusco, A. L. Mahood, Human-started wildfires expand the fire niche across the United States, Proc. Natl. Acad. Sci. U.S.A. 114 (2017) 2946–2951, https://doi.org/10.1073/pnas.1617394114.

[4] X. Zong, X. Tian, J. Liu, A fire regime zoning system for China, Front. For. Glob. Chang. 4 (2021) 1–11, https://doi.org/10.3389/ffgc.2021.717499.

[5] P.E. Dennison, S.C. Brewer, J.D. Arnold, M.A. Moritz, Large wildfire trends in the western United States, 1984-2011, Geophys, Res. Lett. 41 (2014) 2928–2933, https://doi.org/10.1002/2014GL059576.

[6] S.H. Doerr, C. Santín, Global trends in wildfire and its impacts: perceptions versus realities in a changing world, Philos. Trans. R. Soc. B Biol. Sci. 371 (2016), 20150345, https://doi.org/10.1098/rstb.2015.0345.

[7] Y. Touge, M. Hasegawa, M. Minegishi, S. Kawagoe, S. Kazama, Multitemporal UAV surveys of geomorphological changes caused by postfire heavy rain in Kamaishi city, northeast Japan, Catena 220 (2023), 106702, https://doi.org/10.1016/j.catena.2022.106702.

[8] A. Sekizawa, Recent trends in forest fires in Japan, Proc. JAFSE Annu. Symp. (2022) 133–134.

[9] S. Yue, M. Hashino, Temperature trends in Japan: 1900–1996, Theor. Appl. Climatol. 75 (2003) 15–27, https://doi.org/10.1007/s00704-002-0717-1.

[10] S. Yue, M. Hashino, Long term trends of annual and monthly precipitation in Japan, JAWRA J. Am. Water Resour. Assoc. 39 (2003) 587–596, https://doi.org/10.1111/j.1752-1688.2003.tb03677.x.

[11] Fire and Disaster Management Agency, Annual report on fires in Japan, Minist. Intern. Aff. Commun. (2022).

[12] Ministry of Internal Affairs and Communications, Result of the investigation of part-time fire department, Https://Www.Fdma.Go.Jp/Pressrelease/Houdou/Items/221220_chibou_01.Pdf (Accessed 8 Februaryr. 2023). (n.d.)..

[13] J. Kondo, T. Kuwagata, Enhancement of forest fires over Northeastern Japan due to atypical strong dry wind, J. Appl. Meteorol. 31 (1992) 386–396, https://doi.org/10.1175/1520-0450(1992)031<0386:EOFFON>2.0.CO;2.

[14] Forestry Agency, Annual Report on Forest and Forestry in Japan, 2021. https://www.rinya.maff.go.jp/j/kikaku/hakusyo/r3hakusyo/index.html.

[15] Statistics Bureau of Japan, National Census in, 2020. Https://Www.Stat.Go.Jp/Data/Kokusei/2020/Index.Html. (Accessed 8 February 2023). n.d.

[16] Latest tobacco information, Smoking rate for adult, Https://Www.Health-Net.or.Jp/Tobacco/Statistics/Kokumin_kenkou_eiyou_report.Html (Accessed 8 Februaryr. 2023). (n.d.)..

[17] Tokyo Hourei Ltd, Handbook of Fire Statistics, 2007.

[18] L. N.M, D.B.R.A.P. Dempster, Maximum likelihood from incomplete data via the EM algorithm, J. R. Stat. Soc. Ser. B. 39 (1977) 1–38.

[19] C. Fraley, A.E. Raftery, Model-based clustering, discriminant analysis, and density estimation, J. Am. Stat. Assoc. 97 (2002) 611–631, https://doi.org/10.1198/016214502760047131.

[20] S. Yue, C.Y. Wang, Applicability of prewhitening to eliminate the influence of serial correlation on the Mann-Kendall test, Water Resour. Res. 38 (2002), https://doi.org/10.1029/2001WR000861, 4-1-4–7.

[21] K. Shi, Y. Touge, Identifying the shift in global wildfire weather conditions over the past four decades: an analysis based on change-points and long-term trends, Geosci. Lett. 10 (2023), https://doi.org/10.1186/s40562-022-00255-6.

[22] O. Pechony, D.T. Shindell, Driving forces of global wildfires over the past millennium and the forthcoming century, Proc. Natl. Acad. Sci. U.S.A. 107 (2010) 19167–19170, https://doi.org/10.1073/pnas.1003669107.

[23] H. Kusanagi, Proposal of nine climate regions for Japan using the cluster analysis of the daily-averaged water precipitation, Bull. J. Meteorol. Soc. Japan. 63 (2016) 5–12.

[24] W.M. Jolly, M.A. Cochrane, P.H. Freeborn, Z.A. Holden, T.J. Brown, G. J. Williamson, D.M.J.S. Bowman, Climate-induced variations in global wildfire danger from 1979 to 2013, Nat. Commun. 6 (2015) 1–11, https://doi.org/10.1038/ncomms8537.

[25] R.G. Haight, J.S. Fried, Deploying wildland fire suppression resources with a scenario-based standard response model, INFOR 45 (2007) 31–39, https://doi.org/10.3138/infor.45.1.31.

[26] S. Sakellariou, M.A. Parisien, M. Flannigan, X. Wang, B. de Groot, S. Tampekis, F. Samara, A. Sfougaris, O. Christopoulou, Spatial planning of fire-agency stations as a function of wildfire likelihood in Thasos, Greece, Sci. Total Environ. 729 (2020), 139004, https://doi.org/10.1016/j.scitotenv.2020.139004.

[27] Ministry of Agriculture Forestry and Fisheries, Management of ponds in each Prefecture, Https://Www.Maff.Go.Jp/j/Nousin/Bousai/Bousai_saigai/B_tameike/Tameike_taiou.Html (Accessed 8 Februaryr. 2023). ((n.d.)).

[28] S. Watanabe, Y. Itsumi, K. Yasuda, M. Asano, H. Morikawa, S. Ishida, Y. Kuwana, M. Kimura, Current status and issues related to agricultural pond management – a case report of Tanbara, Saijo, Ehime, J. JAPAN Soc. Hydrol. WATER Resour. 34 (2021) 127–135, https://doi.org/10.3178/jjshwr.34.127.

[29] K. Shi, Y. Touge, S. Kazama, Defining homogeneous drought zones based on soil moisture across Japan and Teleconnections with large-scale climate signals, J. Appl. Meteorol. Climatol. 61 (2022) 43–60, https://doi.org/10.1175/JAMC-D-21-0133.1.

[30] J.E. Keeley, A.D. Syphard, Historical patterns of wildfire ignition sources in California ecosystems, Int. J. Wildland Fire 27 (2018) 781–799, https://doi.org/10.1071/WF18026.