Spatiotemporal Statistics for Analyzing Climatic Conditions Influencing *Lymantria dispar* Outbreaks

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**Abstract:** The spongy moth (*Lymantria dispar*) is a forest pest that damages a variety of trees in North America and Eurasia. A spongy moth outbreak occurred in part of South Korea in 2020 and caused severe damage to domestic forests and human society. Since the occurrence of spongy moths is influenced by climatic factors, this study examines the causes of spongy moth outbreaks by analyzing the temporal and spatial differences in climatic factors, influencing spongy moth occurrence using specimens collected during field surveys. Climatic factors were identified using global occurrence coordinates to compare the weather characteristics of spongy moth occurrence in domestic regions, using the kernel density function. Spatial and temporal comparisons were performed for monthly weather factors obtained from field surveys in 2020 and 2021 in areas with high and low spongy moth larvae densities. Spongy moth outbreaks may result from particular combinations of variable seasonality in temperature and precipitation, including high temperatures during cold periods and low precipitation during developmental periods.

**Keywords:** climatic factors; kernel density function; spongy moth; statistical analysis; weather factors

1. **Introduction**

The spongy moth (*Lymantria dispar*) is an agricultural and forest pest that has caused damage to various crops and trees, as well as health impacts from mass occurrence [1,2]. It is generally found in temperate areas from northern Africa to Eurasia, reaching the Japanese archipelago, and has now been introduced to France and North America [3–5]. In South Korea, spongy moths have been reported throughout the country, except in the southwest regions, causing health concerns in urban residences and forest damage [2,6], thus necessitating the prediction of possible conditions for preventing outbreaks.

Climatic factors have a considerable influence on the distribution and population of insects [7]. Spongy moth habitats are predominantly distributed in temperate regions, suggesting that regional climate determines their distribution range [1]. The effect of climatic conditions on spongy moths is likely a dominant factor influencing their occurrence and population growth [8]. Excessively high or low temperatures which vary by season may increase the mortality of spongy moth eggs, with high precipitation potentially influencing the infection rate for the deadly virus in spongy moths [9–13]. Optimal growth and the survival rate of spongy moth larvae are likely related to temperature, suggesting that spongy moth occurrence is strongly dependent on climatic conditions [14,15].

In 2020, there was a large outbreak of spongy moths in South Korea, causing damage to a wide range of forests and social issues of discomfort due to a large quantity of eggs in residential areas [16,17]. In contrast, spongy moths were not frequently recorded in South Korea in 2019 and 2021, suggesting temporal difference of environments affects the domestic outbreak. In addition, spatial difference of the spongy moth population even in...
2020 outbreak indicates the necessity for examining environmental variability determined as the Moran effect [8]. Therefore, this study examines the climatic characteristics of areas where spongy moths are distributed and identifies the weather factors affecting spongy moth outbreaks through spatial and temporal comparisons based on field surveys in areas with large populations of spongy moths. Findings from this research are expected to provide a baseline to facilitate forecasting future spongy moth outbreaks.

2. Materials and Methods

2.1. Distribution of the Spongy Moth to Extract Climate Data

The global occurrence coordinates for spongy moths were obtained from the Global Biodiversity Information Facility (GBIF) and cross-checked with the Center for Agriculture and Bioscience International (CABI) to confirm reliable occurrence points [18,19]. To remove sampling bias and autocorrelation, spatial filtering was performed using the SDM toolbox in ArcMap (version 10.4.1; ESRI, Redlands, CA, USA), resulting in 3934 occurrence coordinates for the spongy moth [20,21] (Figure 1a). The meteorological data were extracted from the final occurrence coordinates.

![Figure 1. Distribution areas for spongy moths with (a) global occurrence coordinates with actual distribution sites (red dots), and (b) field survey areas with high and low spongy moth density applied for climatic analysis.](image)

2.2. Global Meteorological Data from Areas of Spongy Moth Occurrence

Global climate data including the monthly average temperature, monthly minimum temperature, monthly maximum temperature, and monthly precipitation from 1970 to 2000 were obtained from WorldClim with 1 km resolution (www.worldclim.org (accessed on 6 December 2021)) [22]. As the world climate data were provided as an image file, we first converted it to raster format and then extracted the values for four meteorological data points at the coordinates of occurrence using ArcMap.

2.3. Domestic Weather Data

Weather data at the national scale, including the monthly average temperature, monthly minimum temperature, monthly maximum temperature, and monthly total precipitation, were obtained from the Korea Meteorological Administration (KMA) for January to December 2019–2021 (Figure 1). Given that the spongy moth outbreak occurred in 2020 but it was not observed nationwide in 2019 or 2021, weather data were obtained from 2019 to 2021. The weather data were extracted for six areas with high spongy moth larvae density, or where spongy moths were not observed, to compare the spatial and temporal differences in the weather data.
2.4. Domestic Occurrence Data and Field Survey

The data recording areas with high and low density of spongy moth in 2020 was obtained from the National Institute of Forest Science. This data did not include quantitative population density, but indicated the level of density. A field survey was conducted to investigate the density of gypsy moths from March to September 2021 at six sites with high or low density of the spongy moth (Figure 1b). Field surveys were performed once or twice per month at each site, with burlap traps installed on approximately 20 trees. Species of trapped trees, the host plants of spongy moths, were Acer pseudosieboldianum, Ginkgo biloba, Malus floribunda, Cornus officinalis, Juglans regia, Quercus mongolica, Magnolia kobus, Diospyros kaki and Zelkova serrata [23–25]. Spongy moths were observed in egg masses in March and September, in the larval state from April to June, and in the pupa and adult state from June to August. The samples collected were stored in absolute ethanol at Chungnam National University, Korea. These field surveys were conducted from May to October 2021, using the same method used for the occurrence regions. A total of 1768 eggs and 1133 larvae were found in March and April, respectively, but all disappeared in June and no adults were found at all. In addition, a total of 20 adults were only found in three low-density areas during the whole field survey.

2.5. Statistical Analysis for Global Climatic and Domestic Weather Factors

To analyze the climatic characteristics for areas where spongy moths have been recorded, the kernel density function was used for four types of global climatic data, as well as data from South Korea. By comparing the similarity of the distribution patterns for the meteorological data, climatic characteristics suitable for spongy moth occurrence were spatially examined. For the domestic meteorological data, ANOVA and post-hoc tests (Tukey tests) were used to compare meteorological data for time and locations with high and low density. We examined whether there were significant differences in weather factors for time and regions according to the larval density of spongy moths. The statistical analyses were conducted using R version 4.1.2 after grouping the monthly weather factors for each of the three regions classified by density with a significance level of 0.05 [26].

3. Results

3.1. Characterizing Climatic Conditions Suitable for Spongy Moth Occurrence

The distribution of climatic factors at global occurrence coordinates for spongy moths was analyzed using the kernel density function and temporally compared to areas where the domestic spongy moth outbreak was surveyed (Figure 2). Globally, 90% or more areas showed an average monthly temperature, maximum monthly temperature, minimum monthly temperature, and monthly precipitation of −7–21 °C, 2–27 °C, −11–15 °C, and 30–115 mm, respectively. The maximum frequencies were observed at 17.5 °C, 22.8 °C, 12.2 °C, and 63 mm for average monthly temperature, maximum monthly temperature, minimum monthly temperature, and monthly precipitation, respectively. The range of favorable climatic factors was found to be an average monthly temperature of 10–20 °C, with an optimal maximum range of 0–25 °C.

For weather factors extracted from the domestic field survey areas from 2020, when the spongy moth outbreak was reported, the temperature ranges were estimated to be from −30 °C with the highest frequency at 6.5 °C, 25.2 °C, −0.3 °C, and 34 mm for the average monthly temperature, maximum monthly temperature, minimum monthly temperature, and monthly precipitation, respectively. In 2021, when there was no spongy moth outbreak in South Korea, there was an average temperature range of −3–25 °C with a maximum frequency of 15.8 °C. The average maximum and minimum temperatures were 3–29 °C, and −8–21 °C, respectively, while the monthly precipitation range was 6–237 mm with maximum frequencies of 41.8 mm.
Figure 2. Kernel density distribution of the major climatic factors in global occurrence coordinates obtained for 30 years (1970–2000), and in domestic field surveys in 2020 and 2021. Dark blue areas include 90% of the total distribution with 5% and 95% of the lower and upper threshold, respectively (X-axis has the unit of temperature (°C), and precipitation (mm), while Y-axis shows the kernel density).

When comparing the domestic weather characteristics of the area where the spongy moth occurred in 2020 and the global distribution areas, the global distribution was lower than in South Korea in 2020, suggesting that the South Korean temperatures were higher than the conditions to which the species has been adapted. The precipitation distribution encompassed a wider range with high variation, which suggests high precipitation seasonality in 2020, when spongy moth occurrence was high. The global and domestic climate distribution overlap over a wide range and variation patterns are similar, suggesting the potential for the use of climatic preference as a factor in determining the distribution of spongy moths. The distribution of weather factors in 2021, when there was no outbreak, was similar to that of 2020, except for precipitation.

3.2. Spatial Analysis of Domestic Weather Conditions

The kernel density function is useful for identifying favorable weather conditions, but a similar distribution range suggests that it is necessary to analyze outbreak factors using more detailed weather data. In this study, detailed weather factors were recorded monthly during one year for the field survey areas with and without spongy moth outbreaks, which were statistically compared to consider spatial differences. As a result, all four weather factors were found to be significantly different during the winter season, while precipitation and maximum temperature were or were not different depending on the
month (Table 1). Statistically significant differences were found for all weather factors in December, and each temperature factor showed a difference of 4–5 °C and precipitation of approximately 6 mm. Temperature factors for November, January, and February differed by location, suggesting that winter temperatures may have affected the spongy moth outbreak. Significant differences were observed for precipitation in February, March, July, September, and December. March precipitation decreased by approximately 40 mm compared with February in high-density areas, which was not reported in low-density areas. There was a significant difference despite the small difference in average precipitation in March compared with other months, suggesting that there was little variation.

3.3. Temporal Analysis of Domestic Weather Conditions

A temporal comparison was conducted for weather factors in 2020, when there were many spongy moths, and in 2019, and 2021, when there were few spongy moths (Table 2). A highly significant difference was observed for precipitation, which differed during the winter and spring seasons, in addition to during August and October. Precipitation was substantially higher in January, February, and August, but was lower from March to May and October. A significant difference can be seen in the precipitation in January and February, which is the winter season. However, since the spongy moth remains as eggs during this season, the effect of precipitation might be less than that of temperature. For temperature, a significant difference was only found during the winter season by approximately 2–6 °C according to month, and the most substantial difference was observed for the minimum temperature in January. In January, all four weather factors were different, with temperatures 2–6 °C lower in 2020 than in 2019 and 2021, with a higher precipitation of approximately 50 mm. As suggested by findings from the spatial comparison, the temperature during the winter season may affect spongy moth outbreaks.
Table 1. Spatial analysis of weather data in areas with high and low spongy moth density in 2020.

| Weather Factor                  | Density  | Jan.  | Feb.  | Mar.  | Apr.  | May   | Jun.  | Jul.  | Aug.  | Sep.  | Oct.  | Nov.  | Dec.  | Average |
|--------------------------------|----------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|---------|
| Monthly average temperature (°C) | High     | 1.1   | 3.9   | 6.9   | 10.9  | 17.1  | 22.5  | 22.4  | 25.3  | 19    | 11.9  | 6.8   | –2    | 11.9   |
|                                | Low      | 2.1   | 4.6   | 8.3   | 10.9  | 17.8  | 22.6  | 22.7  | 27.2  | 20.7  | 14.8  | 9.8   | 2     | 13.8   |
| Monthly maximum temperature (°C) | High     | 6.4   | 7.7   | 13.7  | 16.9  | 23   | 28.1  | 26.4  | 29.5  | 24.1  | 18.8  | 12.9  | 3.9   | 17.6   |
|                                | Low      | 8.5   | 10.2  | 14.8  | 17.7  | 23.4  | 28   | 26.5  | 31.5  | 25.7  | 21.2  | 15.4  | 7.7   | 19.2   |
| Monthly minimum temperature (°C) | High     | –3.3  | –3.1  | 0.2   | 2.8   | 11.6  | 17.4  | 19   | 22.2  | 14.9  | 6    | 1.3   | –7.1  | 6.8    |
|                                | Low      | 0.2   | –0.3  | 2.1   | 4.6   | 12.9  | 18.1  | 20.1  | 24   | 16.8  | 9.5   | 5     | –2.6  | 9.2    |
| Precipitation (mm)             | High     | 59.7  | 60.1  | 20.3  | 93.7  | 95.6  | 277.9 | 516.9 | 156.5 | 10.5  | 36.6  | 4.7   | 112.7  |
|                                | Low      | 79.1  | 41.8  | 45.6  | 126.5 | 252.3 | 463.9 | 448.5 | 225.5 | 20    | 32.3  | 11.1  | 150    |

Data with different letters mean a significant difference in monthly factors between regions based on the Tukey’s test.

Table 2. Temporal weather data analysis in areas with high spongy moth density in 2019, 2020, and 2021.

| Weather Factor                  | Year   | Jan.  | Feb.  | Mar.  | Apr.  | May   | Jun.  | Jul.  | Aug.  | Sep.  | Oct.  | Nov.  | Dec.  | Average |
|--------------------------------|--------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|---------|
| Monthly average temperature (°C) | 2019   | –2.2  | 0.6   | 5.9   | 10.7  | 17.6  | 20.7  | 24.1  | 24.9  | 20.4  | 14    | 6.4   | 0.6   | 12     |
|                                | 2020   | 1.1   | 2.1   | 6.9   | 10.9  | 17.1  | 22.5  | 22.4  | 25.3  | 19    | 11.9  | 6.8   | –2    | 11.9   |
|                                | 2021   | –3.4  | 1.6   | 7.6   | 12.2  | 15.1  | 20.7  | 25    | 23.2  | 19.8  | 13.2  | 6.6   | 0.2   | 11.8   |
| Monthly maximum temperature (°C) | 2019   | 4.3   | 6.7   | 12.9  | 17.7  | 25.4  | 26.9  | 28.8  | 30.3  | 25.6  | 20.1  | 13.5  | 6.1   | 18.2   |
|                                | 2020   | 6.4   | 7.7   | 13.7  | 16.9  | 23   | 28.1  | 26.4  | 29.5  | 24.1  | 18.8  | 12.9  | 3.9   | 17.6   |
|                                | 2021   | 2.6   | 8.1   | 14   | 18.5  | 20.9  | 30.2  | 27.7  | 24.7  | 19.5  | 13.2  | 5.9   | 17.6   |
| Monthly minimum temperature (°C) | 2019   | –8.3  | –4.8  | –0.5  | 3.9   | 9.5   | 15    | 20.2  | 20.5  | 16    | 8.5   | 0.6   | –4.1  | 6.4    |
|                                | 2020   | –3.3  | –3.1  | 0.2   | 2.8   | 11.6  | 17.4  | 19    | 22.2  | 14.9  | 6    | 1.3   | –7.1  | 6.8    |
|                                | 2021   | –9.2  | –4.4  | 1.5   | 5.6   | 9.5   | 16    | 20.2  | 19.5  | 15.5  | 8.4   | 1.5   | –4.8  | 6.7    |
| Precipitation (mm)             | 2019   | 2.3   | 26.8  | 34.5  | 49.2  | 23.9  | 103.2 | 189.6 | 116.7 | 151.4 | 81.3  | 80.4  | 15.2  | 72.9   |
|                                | 2020   | 59.7  | 60.1  | 20    | 20.3  | 93.7  | 95.6  | 279.9 | 516.9 | 156.5 | 10.5  | 36.6  | 4.7   | 112.7  |
|                                | 2021   | 12.8  | 8.3   | 82   | 78.6  | 156.7 | 82.8  | 164.8 | 210.4 | 198   | 45.6  | 55.9  | 4.4   | 91.7   |

Data with different letters mean a significant difference in monthly factors between regions based on the Tukey’s test.
4. Discussion

In previous studies, the times of spongy moth outbreaks have been studied in relation to various environmental factors, of which climate has been shown to be dominant [27]. Consequently, spatiotemporal analyses of field surveys and weather factors between 2019 and 2021 were conducted in this study to consider weather factors preceding the outbreak in 2020 that were different from those preceding the non-outbreak years of 2019 and 2021. Global and domestic climate factors were not found to significantly favor the outbreak in 2020. However, the domestic weather at the occurrence sites had slightly higher temperature ranges and variable precipitation by season. Compared with the weather at the low-density sites, the weather at the occurrence sites varied with more peaks in the kernel density function, suggesting that seasonal variation in weather may be a factor causing spongy moth outbreaks [4]. The difference between the global occurrence data, including both European and Asian spongy moths, and domestic field surveys collecting Asian spongy moths may have resulted in slight differences in climatic data due to their own biological characteristics [28]. In addition, outbreaks typically progress through several phases, including population growth, peak, and declining years, suggesting the lasting effect of climate. For this reason, it is important to analyze climatic factors with consideration to seasonal variation and spatial presence or absence of a species to determine the reason for the outbreak.

A spatial comparative analysis was performed by selecting an area according to the density of larvae at the time of the spongy moth outbreak in 2020. This was done to confirm the role of weather factors by revealing the effect of weather difference by location, because simple analysis on weather over time in the same site could not explain the spatial difference in 2020. Therefore, we tried to confirm the role of weather factors by showing that climate differences due to spatial differences influence the occurrence of spongy moths. For this analysis, it was possible to identify different weather factors by month, suggesting that the winter weather affected spongy moth outbreaks. The eggs of spongy moths begin to hatch when exposed to a temperature of approximately 10 °C after being exposed to low temperatures [29], suggesting the appropriate hatching timing (March) may be slightly advanced because of the relatively high temperature in February. This means that spongy moth eggs in low-density areas hatch earlier than those in high-density areas. As the larvae hatched earlier in February, when the average monthly temperature was 4.6 °C because of early hatching, the minimum growth temperature of 7 °C was not reached, which likely influenced the larval mortality rate [15]. Monthly precipitation appears to affect the spatial differences in spongy moth outbreaks. Precipitation is a factor that substantially affects the spread of the fungal pathogen Entomophaga maimaiga and the LdNPV virus, which is fatal to spongy moths, and high precipitation limits the population of spongy moths [10,30]. Therefore, high winter temperature and precipitation when spongy moths begin to develop after hatching may result in a low density of spongy moths. Warm winter temperature and adequate precipitation at the time of development may be factors leading to gypsy moth outbreaks. In particular, the high winter temperature, enough to cause early hatching due to the high temperature in winter, was achieved in 2020 in contrast to the normal winter temperature in 2021, causing outbreak of the spongy moth. There might be other factors affecting the spongy moth population, such as topology, host plants, and local biodiversity [31], but they are relatively constant compared with weather factors. In addition, all six sites of the field survey were near mountainous areas, suggesting that surrounding environment was similar. Therefore, a spatial comparison of weather factors could find a potential cause of the spongy moth outbreak.

The temporal comparison confirmed the effect of winter weather on spongy moth outbreaks. The daily minimum temperature in January, the coldest month in South Korea, was approximately −3–6 °C in 2020, while it was −8–4 °C in 2019, and −9–3 °C in 2021. This low winter temperature may have increased the mortality rate with the exposure of spongy moth eggs to extreme weather. If the winter temperature reaches −29 °C, the supercooling point of the spongy moth egg, or if there is a period in which the temperature is maintained
at approximately −15 °C to −20 °C, spongy moth outbreaks may not occur [13]. When considering the high winter temperatures recorded in areas with low density in 2020, it is likely that excessively high or low winter temperatures can inhibit the occurrence of spongy moths. As in the case of spatial analysis, precipitation was significantly different during spring, suggesting high levels of precipitation around the main period of development for the spongy moth larvae after hatching limited spongy moth outbreaks. Moderate winter temperatures and low spring precipitation may cause outbreaks of spongy moths. Consequently, it may be possible to forecast outbreaks of spongy moths in spring based on the previous winter weather. This is helpful for establishing a strategy for monitoring and controlling the spongy moth, which can subsequently reduce losses in forests and agriculture, including the fruit industry that suffers due to spongy moth outbreaks.

Although weather factors were analyzed as major factors influencing the occurrence of spongy moths in South Korea, the population density of the Lepidoptera family, which has a cyclic population, is known to be affected by parasitoids [32]. Previous studies have suggested that weather factors such as temperature and precipitation were related to the population of parasitoids [33,34], suggesting the role of weather and climate factors on the spongy moth population. In contrast, another study showed less correlation between parasitoids population and weather factors [35]. Since Lepidopteran populations are often cyclic, usually with long time intervals of outbreak [32], long-term observation may be required to accurately identify the outbreak of the gypsy moth. Compared to the species distribution modeling method that directly evaluates potential distribution of a species, this climate analysis method cannot directly predict the potential distribution area. However, it can easily identify the climatic characteristics of the habitat area without a complex modeling process, and can identify noticeable climatic differences through quantitative comparisons. Therefore, a more reliable result can be produced by comparing the climatic characteristics of the potentially habitable area through the prediction by species distribution modeling and data based on distribution information [36,37].

5. Conclusions

In this study, we aimed to determine the cause of spongy moth outbreaks in South Korea by analyzing the climatic conditions. There are some drawbacks in this study, including the absence of quantified population density applicable for investigating the correlation between meteorological factors and population, a limited number of sites, and other environmental factors that affect spongy moth development. However, this study applied simple spatiotemporal statistics which did not require quantitative population data to explore the role of climatic factors, and proposed potential reasons for the outbreak, which were winter weather and spring precipitation, along with weather seasonality. According to data released by the Korea Meteorological Administration, winter temperatures in 2020 were abnormally high throughout the country, with an average of 3.1 °C, the warmest winter since 1973. The increase in mortality due to the cold winter weather did not occur in areas with spongy moth outbreaks, whereas in the southern regions, the early hatching time accelerated due to the excessively hot winter temperatures likely inhibiting spongy moth occurrence due to insufficient food supplies. High precipitation during the spring season increases fungal pathogens, limiting the development of spongy moths. Therefore, outbreaks of spongy moths can be forecasted through the analysis of climate factors in winter and spring, which is helpful for establishing a control strategy.

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