Fire Risk Assessment in the Guangxi region of China Based on SMAP Soil Moisture Data

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Abstract: A fire risk assessment for the Guangxi region of China in 2024 is carried out in this study using Soil Moisture Active Passive (SMAP) satellite data. Specifically, by analyzing the relationship between the SMAP soil moisture and the number of fire points, we develop a fire risk assessment method based on soil moisture conditions. The spatio-temporal distributions and variation patterns of fire points in Guangxi are evaluated from the perspectives of multiple time scales, different soil moisture statistics and varying fire durations, providing scientific reference and technical support for early warnings of disasters such as forest and grassland fires. The results indicate that SMAP soil moisture data effectively reflect the dryness of surface combustible materials. A prominent negative correlation is observed between the number of fire points and soil moisture content, although the correlations vary with time scales and remain below 0.6 (R2). The correlation at the monthly scale is markedly stronger than that at the ten-day and daily scales. Compared with the values of soil moisture, the regional relative deviation of soil moisture has a stronger correlation with the number of fire points, with R2 values reaching 0.744, 0.763 and 0.922 at the day, ten-day and monthly scales, respectively. Statistics further reveal that for every 10% decrease in soil moisture content, the number of fire points in Guangxi in 2024 can increase by over 50%. These findings demonstrate that soil moisture plays an important role in fire risk assessment, and the assessment methods based on SMAP soil moisture data has promising potential in fire risk analysis.

Keywords: Fire risk assessment; Soil moisture; Soil Moisture Active Passive (SMAP); the Guangxi region

1. Introduction

Forest and grassland fires, as natural disasters, pose serious threats to ecological environments, socio-economic development, and the safety of human life and property. The Guangxi region of China, characterized by high forest coverage, relies heavily on its forest resources to ensure ecological security. However, the frequent occurrence of forest fires poses notable risks to forest resources, the environment and public safety [1–3]. Accurate prediction of forest fire risk levels is an important part of fire prevention and control and is essential for effectively preventing fires and reducing fire-related losses. Satellite remote sensing has been a critical tool for fire detection and has been increasingly applied in forest fire management in recent years [4–6]. The moisture content of surface dead combustibles plays a vital role in fire risk prediction. However, there are relatively few studies on the retrievals of dead understory fuels based on microwave remote sensing. Most studies rely on ground-based point measurements [7], which are inadequate for large-scale and high-temporal-resolution observations. Soil moisture is a key factor influencing the moisture content of surface fuels, especially dead combustibles in direct contact with the soil. Soil moisture can indirectly reflect the flammability of surface dead combustibles, and thus it serves as a critical factor in forest fire risk prediction models. Therefore, Soil Moisture Active Passive (SMAP) soil moisture products have emerged as valuable datasets for fire risk assessment and analysis [8–9].

The SMAP satellite, launched by the National Aeronautics and Space Administration (NASA), is an important mission for global soil moisture monitoring. Equipped with L-band microwave sensors, it provides high-resolution and high-precision soil moisture data, offering a new approach and a new data source for regional-scale fire risk research. Currently, meteorological forest fire risk prediction models are the primary approach for forest fire risk prediction in Guangxi and surrounding areas. However, relying solely on meteorological elements makes it difficult to capture the actual moisture content of combustibles in the forest. To improve the prediction performance of fire risk models, this study evaluated the spatio-temporal distributions and variation patterns of fire points at different time scales, various soil moisture statistics and fire event durations using the SMAP soil moisture observations and fire point data obtained from satellite remote sensing in 2024. This study aims to explore the application of SMAP soil moisture products in fire risk analysis, investigate the relationship between soil moisture and fire occurrences and develop an effective fire risk prediction method.

The remainder of this paper is arranged as follows. Section 2 introduces the study area. Section 3 shows the data used in this research and the data processing methods. Section 4 presents the analysis results, and section 5 provides the main conclusions and discussion.

2. Study Area

2.1 Geographical and Geomorphological Features of Guangxi

Guangxi is characterized by a basin-like landscape composed primarily of mountainous and hilly terrain. It is surrounded by mountains and plateaus, and its central and southern regions consist mainly of hills and flatlands, forming a topography that resembles a basin. The overall terrain is generally higher in the northwest and lower in the southeast. The mountains are mainly distributed in an arc shape, presenting a multi-layered nested structure, and the distribution of hills is complex and interlaced. The elevation of the study area is shown in Figure 1. This diverse terrain and landscape lead to distinct regional differences in hydrothermal conditions, soil types and vegetation distribution, all of which have substantial influences on the spatio-temporal distributions of soil moisture and the potential occurrence of fire hazards.

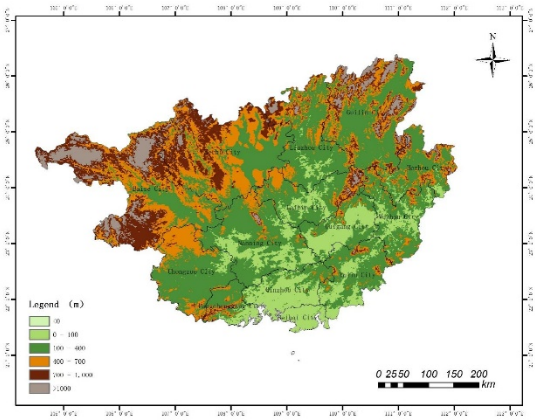

Figure 1: Elevation distribution in Guangxi, China.

2.2 Climate Conditions

Guangxi is located in a low-latitude region, with the Tropic of Cancer traversing its central part. It belongs to the subtropical monsoon climate zone, characterized by warm and humid conditions, abundant rainfall and ample sunshine. Summers are long, with extended sunshine duration, high temperature and abundant precipitation. Winters are relatively short, with reduced sunshine duration and generally dry and mild weather conditions. Precipitation in Guangxi is unevenly distributed both temporally and spatially. Rainfall is concentrated in the summer months, leading to peak river runoff during the flood season. In contrast, some areas experience scarce precipitation during the dry season, increasing the risk of meteorological drought. Figure 2 displays the monthly average soil moisture variation in Guangxi during 2024. These complex and variable climatic conditions in Guangxi profoundly affect the dynamic variations of soil moisture, which is closely related to fire risk levels. During drought periods, rapid evaporation leads to sharp decreases in soil moisture, thereby increasing the probability of fires. Conversely, during periods of abundant rainfall, soil moisture is replenished, and thus fire risk levels decrease.

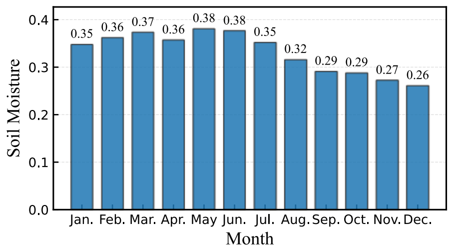

Figure 2: Monthly average soil moisture content in Guangxi during 2024.

2.3 Vegetation Coverage

Guangxi boasts diverse vegetation types, with the zonal vegetation dominated by subtropical evergreen broad-leaved forests, which are primarily distributed in low-altitude mountainous and hilly areas. The region exhibits high vegetation coverage and abundant forest resources, resulting in substantial surface fuel loads that can lead to large-scale wildfires once a fire occurs. Different vegetation types vary in their capacity to conserve soil moisture. Forest vegetation, with its well-developed root systems, can effectively retain soil moisture, whereas grassland vegetation exhibits relatively weaker moisture-retention capacity. Moreover, vegetation growth and spatial distribution patterns are also influenced by soil moisture, which in turn indirectly affects the likelihood of forest fires.

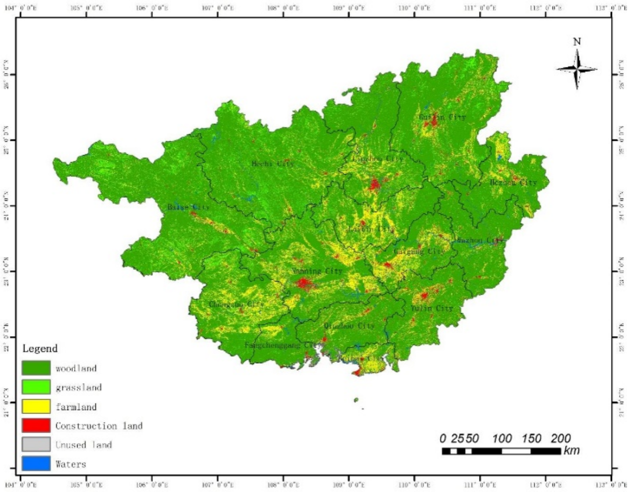

Figure 3: Land use/cover distribution in Guangxi.

3. Data and Processing Methods

3.1 Overview of SMAP Soil Moisture Products

The SMAP satellite, launched by the NASA in January 2015, is specifically designed for global soil moisture monitoring. It is equipped with an L-band active radar and a passive microwave radiometer. Its primary mission is to acquire high-precision global data of surface soil moisture and soil freeze-thaw states [10]. By integrating advanced active microwave detection (radar) and passive microwave detection (radiometer) technologies, SMAP can accurately monitor the soil moisture content in the surface layer (0–5 cm) from multiple observation angles [11]. This capability allows it to capture the dynamic variations in soil moisture in near real time, providing essential data support for regional fire risk analysis. The data are publicly available from the National Snow and Ice Data Center. The key features of the SMAP products relevant to fire risk assessment are detailed as follows.

High spatial resolution: The SMAP microwave radiometer provides data at a spatial resolution of up to 9 km. In Guangxi, where the terrain and vegetation types are highly complex, high-resolution soil moisture data offer a more accurate representation of local soil moisture conditions, enabling better identification of high-risk fire-prone areas. In mountainous regions or areas with an uneven vegetation distribution, differences in soil moisture across land parcels can be clearly distinguished, providing a refined data foundation for fire risk assessment.

High measurement accuracy: The SMAP satellite is equipped with an L-band microwave radiometer, which provides superior penetration compared with X-band and C-band sensors. Therefore, the SMAP microwave radiometer performs better in retrieving soil signals beneath forest canopies. Various studies have demonstrated that SMAP soil moisture data have high accuracy and relatively low error margins, which are crucial for fire risk analysis. Accurate soil moisture data can more reliably characterize the dryness of surface dead combustibles, thereby improving the prediction accuracy of fire risk levels.

Long-term temporal coverage: The SMAP satellite provides continuous observations and has accumulated extensive long-term datasets. This allows for detailed investigation of seasonal and inter-annual soil moisture variabilities in Guangxi, as well as the temporal correlation between soil moisture dynamics and fire risk. Additionally, such data enable the assessment of the influences of seasonal variations in soil moisture on fire risk levels, and the associated linkage between multi-year soil moisture anomalies and major fire events. SMAP soil moisture data provide a basis for research on the lead time for fire risk prediction and early warning.

3.2 Data Processing and Statistical Methods

In addition to SMAP soil moisture data, this study incorporates the fifth-generation European Centre for Medium-Range Weather Forecasts reanalysis (ERA5) Land meteorological data, which include hourly meteorological elements such as temperature, precipitation, wind speed and relative humidity. As a reanalysis dataset, the ERA5-Land data were derived from the land surface component of the ERA5 climate reanalysis dataset, and are widely used in research on climate anomalies and long-term climate variation trends [12–13]. Topographic data, such as elevation, slope and aspect, are also involved. The historical fire point data are derived from the Himawari-9 satellite observations at a 10-minute interval in 2024, as extracted by the National Satellite Meteorological Center, including time, location, active fire area and fire observation frequency [14–15].

During data processing, SMAP soil moisture data underwent rigorous quality control, with invalid values and outliers filtered out according to quality flags. Using the spatial analysis tool of the geographic information system (GIS), SMAP soil moisture data were spatially matched and integrated with multi-source data, namely meteorological, topographic and historical fire point datasets. Statistical analysis methods are employed to quantify the correlation between the SMAP soil moisture and the number of historical fire points. Pearson correlation coefficients are calculated, as shown in Eq. (1), to determine whether a significant negative correlation exists between soil moisture and the number of fire points, thereby revealing the underlying patterns between soil moisture variations and fire risk levels.

$$R = \frac{\sum_{i=1}^{n}(X_i - \overline{X})(Y_i - \overline{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \overline{X})^2}\sqrt{\sum_{i=1}^{n}(Y_i - \overline{Y})^2}} \tag{1}$$

where X_i and Y_i denote the i-th observations of variables X and Y, respectively. $\overline{X}$ and $\overline{Y}$ indicate the means of variables X and Y, respectively. n represents the total number of observations.

In addition, using the GIS spatial analysis tool, soil moisture data are overlaid with the terrain data and the historical fire point data to investigate the spatial distribution patterns of soil moisture under different terrain conditions in Guangxi. In this way, the intrinsic relationship between soil moisture and fire occurrence locations is investigated. Moreover, through spatial statistical analysis, we identify the correlation between high fire-risk areas and soil moisture conditions, aiming to determine specific soil moisture thresholds under which fires are more likely to occur.

4. Results and Analysis

4.1 Spatio-Temporal Distributions of Soil Moisture

Monthly average SMAP soil moisture data from 2015 to 2024 are selected and analyzed to investigate the spatio-temporal distribution characteristics of soil moisture in Guangxi. The results show remarkable spatio-temporal variabilities. Over the past decade, the monthly average soil moisture statistics indicate that the soil moisture content was relatively high from April to June due to abundant rainfall. In contrast, during October to December, a period marked by less precipitation and lower temperature, the soil moisture content was at its lowest level throughout the year. Spatially, high soil moisture zones closely align with areas with higher elevation and dense vegetation cover.

This indicates that the spatial distribution of soil moisture is highly affected by topography and vegetation coverage. In mountainous areas with greater precipitation and higher vegetation coverage, soil moisture is generally higher than that in plain areas. Densely vegetated areas, such as forest regions, exhibit a stronger capacity for soil moisture conservation, leading to relatively higher soil moisture content (Figure 4).

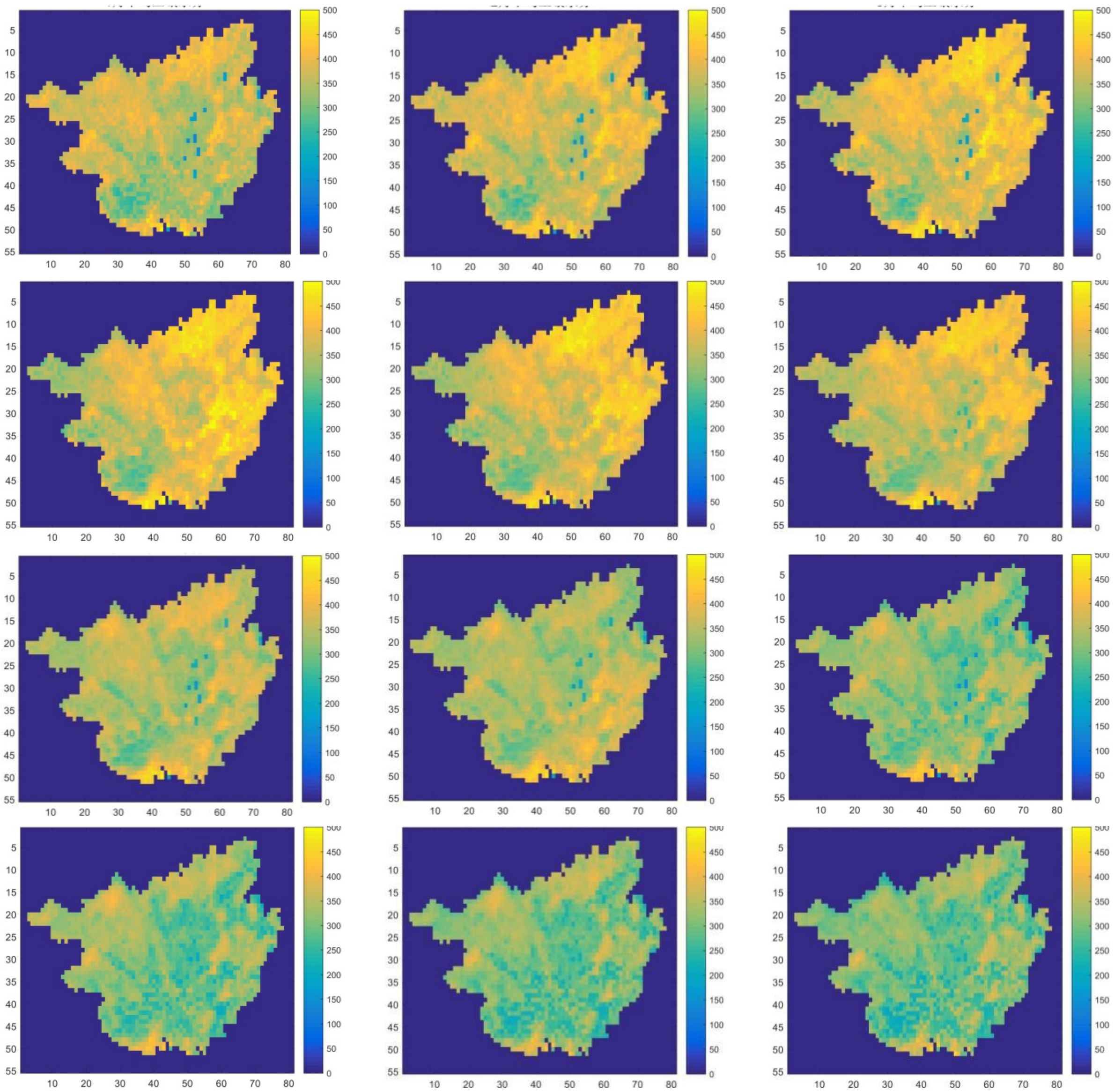

Figure 4: Distribution of monthly average soil moisture in Guangxi from 2015 to 2024.

4.2 Statistical Analysis of Soil Moisture and Fire Points

According to the observations at a 10-minute interval from the Himawari-9 satellite, a total of 5,213 fire points were identified across Guangxi in 2024. The monthly statistics show that 83.4% of these fire points appeared in January–March and October–December (Figure 5). Spatially, the fire points were mainly concentrated in Baise City of western Guangxi, and Liuzhou and Wuzhou Cities of eastern Guangxi. In other areas, the fire points were relatively scattered. The distribution pattern reveals more fire points in the east and west parts of Guangxi and fewer in the north and south (Figure 6). Overall, peak fire occurrences coincided with periods of low soil moisture. There were more fire points in spring and winter when soil moisture was lower, and fewer in summer and autumn when soil moisture was relatively higher (Figure 7).

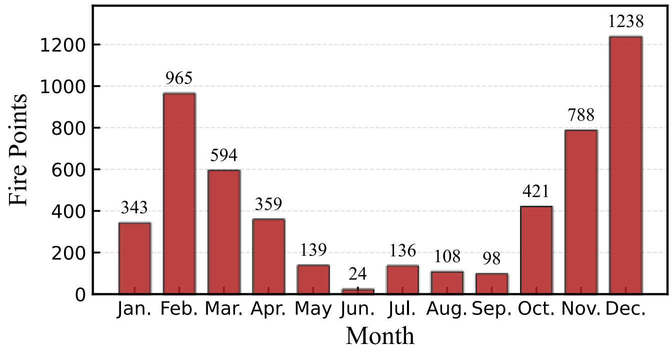

Figure 5: Monthly number of fire points in Guangxi in 2024.

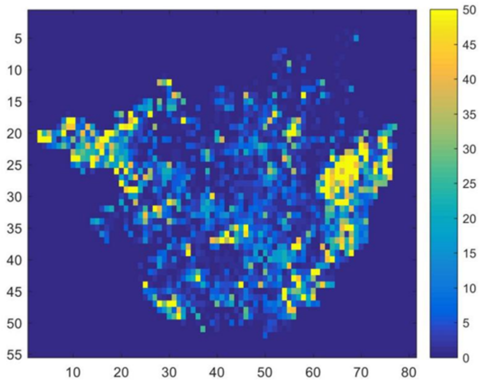

Figure 6: Distribution of cumulative fire point counts from satellite remote sensing observations in Guangxi in 2024.

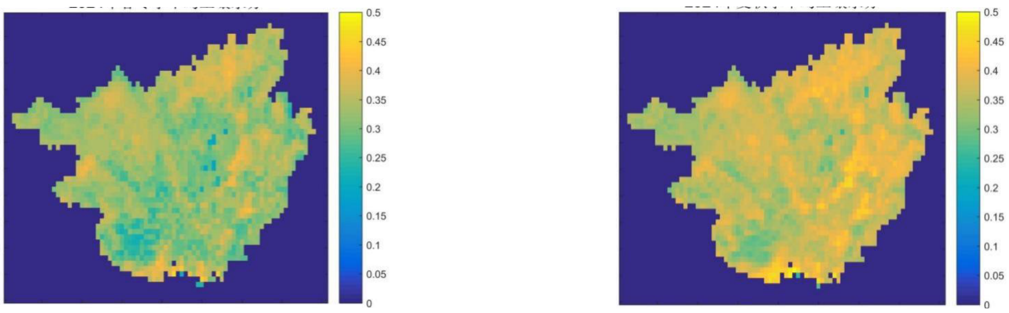

Figure 7: Soil moisture distribution in the winter (left) and summer (right) of 2024.

To quantitatively examine the influence of soil moisture on fire occurrence, statistical analyses were conducted across three temporal scales (daily, ten-day and monthly), considering different statistical values (both absolute values and relative deviations) of soil moisture and different durations of fire points.

(1) Different time scales

Analyses across daily, ten-day, and monthly time scales indicate that soil moisture is negatively correlated with the fire point number, although the correlation coefficients (R2) are all below 0.6. As soil moisture decreases, surface combustibles become dry, thus increasing fire risk. Conversely, when soil moisture increases, the fire occurrence frequency largely decreases. However, the correlation between the fire point number and soil moisture varies notably across different time scales. The monthly scale shows the strongest and most consistent negative correlation pattern compared with the daily scale (Figure 8).

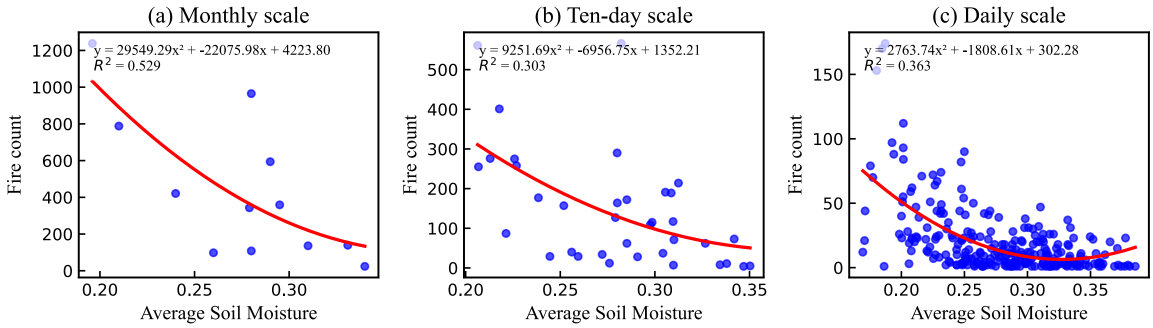

Figure 8: Relationships between the number of fire points and the average soil moisture content at (a) day, (b) ten-day and (c) monthly scales.

(2) Different soil moisture statistical metrics

Statistical results indicate a certain relationship between soil moisture and the number of fire points. However, fire occurrence is also related to other factors such as phenology and traditional fire-use periods. To reduce the interference from these confounding factors, this study introduces a relative deviation metric of soil moisture for statistical analysis, as presented in Eq. (2).

$$\mathrm{Bias_{smc}} = \frac{\mathrm{abs}(\mathrm{SMC}_i - \overline{\mathrm{SMC}})}{\overline{\mathrm{SMC}} * 100\%} \tag{2}$$

where $\mathrm{Bias_{smc}}$ denotes the percentage of the average absolute relative deviation of soil moisture, SMC_i indicates the soil moisture at the location of the i-th fire point, and $\overline{\mathrm{SMC}}$ represents the regional average of soil moisture.

As shown in Figure 9, consistent trends are observed between the fire point number and the soil moisture at daily, ten-day and monthly scales, and the R2 values between the fire point number and the relative deviations of soil moisture reach 0.744, 0.763, and 0.922 at daily, ten-day and monthly scales, respectively. Compared with the absolute value of soil moisture, the relative deviation of soil moisture shows a stronger and nonlinear correlation with the number of fire points. When the relative deviation of soil moisture exceeds a certain threshold, the number of fire points increases sharply. This can be explained by the fact that during phenologically unfavorable and low fire-use periods, the probability of a fire occurring is not necessarily high even if the soil moisture is relatively low. However, during the period when fire points appear, the likelihood of a fire substantially increases in areas with low soil moisture. In other words, in the same areas, fire points tend to appear at locations with relatively lower soil moisture. For example, the daily scale fitting curves suggest that in the same area, when the relative deviation is below 10%, the number of fire points does not exhibit a clear pattern. However, when the deviation exceeds 12%, a 10% decrease in soil moisture can result in a 53% increase in the number of fire points, as shown in Eq. (3).

$$Y_{\mathrm{fire}} = 0.153 * X_{\frac{\mathrm{bias}}{\mathrm{smc}}}{}^{2} - 3.622 * X_{\mathrm{bias-smc}} + 34.825 \tag{3}$$

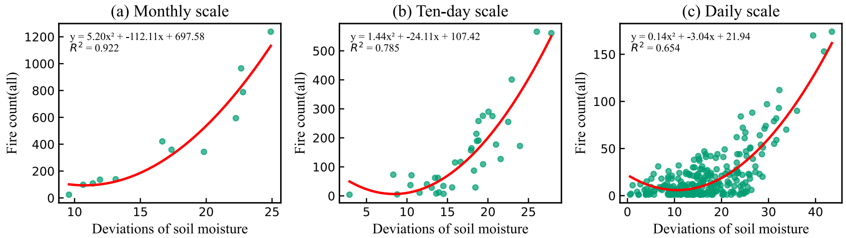

Figure 9: Correlations of the fire point number with the relative deviations of soil moisture at (a) daily, (b) ten-day and (c) monthly scales.

(3) Different durations of fire points

The analysis of the durations of fire points in 2024 suggests that most fire points (64.6%) were detected only once (i.e., lasted less than 10 minutes), indicating that most of the fire points detected by satellite remote sensing were short-lived and small in scale. Fire points lasting more than one hour accounted for less than 6% of the total (Fig. 10). In terms of monthly variations, the number of forest fires lasting more than one hour is proportional to the total number of fire points (Fig. 11). The more fire points there are, the higher the probability of a long-duration fire. This implies that the risk of large-scale forest fires markedly increases during periods of frequent fire activity.

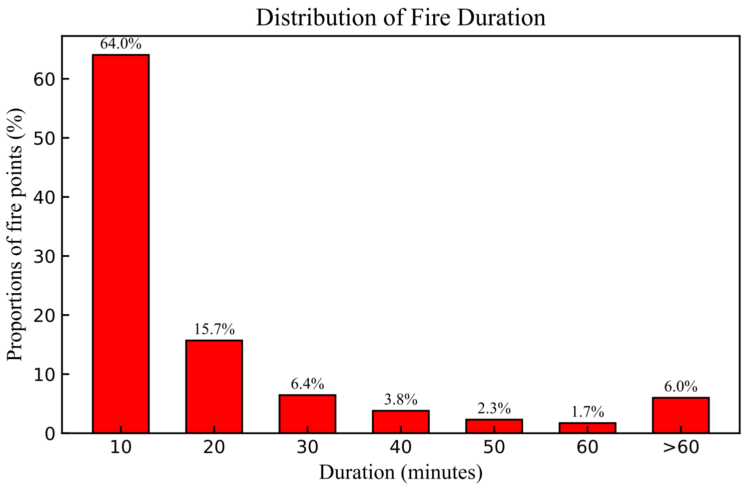

Figure 10: Proportions of fire points with different durations.

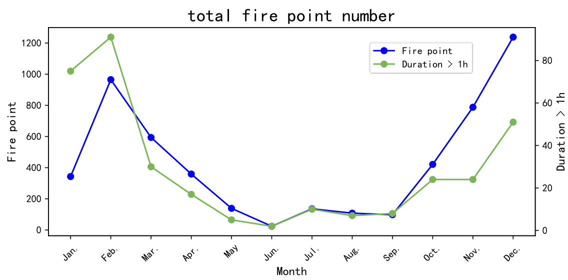

Figure 11: Comparison of the monthly time series between the long-duration fire point number and the total fire point number during 2024.

Using one hour as the threshold, the fire points are categorized into two groups according to their durations (⩽1 hour and >1 hour). As shown in Fig. 11, the number of short-duration fire points (⩽1 hour) is closely related to the relative deviation of soil moisture, showing significant positive correlations across all three times scales. In contrast, large fire points with a longer duration (>1 hour) show a weak correlation at the daily scale, but relatively stronger correlations at ten-day and monthly scales. This demonstrates that at the daily scale, fire development is highly random, influenced by additional factors beyond soil moisture. However, statistics at ten-day and monthly scales can better reflect the influence of soil moisture.

5. Conclusions and Discussion

5.1 Conclusions

Based on SMAP soil moisture data and the fire point monitoring from geostationary satellites, this study conducts an in-depth investigation into fire risk in Guangxi, integrating multi-source data and multi-perspective analytical methods. Through a series of processes including data acquisition, preprocessing, correlation analysis, spatial analysis and model construction, the relationship between soil moisture and fire risk in Guangxi is revealed. The main conclusions are as follows.

Statistical analyses at different scales indicate that the overall variation trend in the number of fire points is closely related to soil moisture conditions. A lower soil moisture content corresponds to a higher frequency of fire occurrences. However, the emergence of sporadic fire points exhibits substantial randomness and does not show a strong correlation (R2 of 0.2–0.35) with soil moisture.

Soil moisture is a sufficient but not necessary condition for prolonged fire duration, i.e., low soil moisture does not necessarily lead to frequent long-lasting fires, but areas where long-duration fires occur frequently are generally characterized by low soil moisture.

The correlation analyses of statistical metrics show that, compared with the absolute value of soil moisture, the relative deviation of soil moisture is more strongly correlated with the number of fire points. Absolute soil moisture content is influenced by seasonality, whereas relative soil moisture content reflects regional dryness. Therefore, relatively drier areas are more prone to fire occurrence.

The high correlation between fire occurrence and soil moisture varies notably across different time scales, with the strongest correlation observed at the monthly scale and the weakest at the daily scale. This result highlights the importance of selecting an appropriate statistical time scale in fire risk analysis, as longer temporal scales help reduce the influence of random factors associated with sporadic fire points.

Varying levels of dryness have different influences on fire occurrence. Curve-fitting analyses at daily, ten-day and monthly scales indicate that when soil moisture is approximately 10% drier than average (relative deviation), the number of fire points increases by 53%.

5.2 Discussion

SMAP soil moisture data can effectively reflect the flammability of surface combustibles, offering substantial scientific value for fire risk analysis and holding considerable potential for applications in fire prevention and emergency management. Despite the promising findings of this study, several limitations remain, and future improvements can be considered in the following areas.

Comprehensive analysis of multiple fire risk factors: This study primarily focuses on soil moisture as the core variable, but the occurrence of fire is influenced by other factors such as climate, phenological conditions, local cultural practices and seasonal customs. These elements warrant further investigation.

Quantitative application of the relative deviation of soil moisture: In this research, the relative deviation of soil moisture exhibits a stronger correlation with the number of fire points than the absolute values of soil moisture. Further research could explore this aspect in greater depth by quantifying the relationship between fire point number and soil moisture variations.

Development of a soil moisture-based fire risk assessment model: This study primarily conducts statistical analyses of fire risk factors and fire point counts to investigate the relationship between soil moisture and fire risk. However, a comprehensive fire risk assessment model has not yet been established. Future work could leverage big data, combined with machine learning and deep learning techniques, to build fire risk prediction models under varying seasonal, phenological and socio-cultural conditions.

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