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Greenhouse Gases Produced During Forest Fires in the La Niña and El Niño Periods in South Sumatra Province

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Abstract

South Sumatra Province has characteristics that significantly increase hotspots and produce greenhouse gas (GHG) emissions in strong El Niño phenomena. This study investigates the impact of forest fires on GHG emissions during extreme climate in the South Sumatra Province from 2010 to 2020. This research analyzes the effects of La Niña and El Niño on the region by analyzing factors such as precipitation patterns, temperature fluctuations, hotspots, and greenhouse gas emissions. This study indicates that forest fires mostly happen during the dry season (May to October). El Niño occurred for the second time in 2015–2016 and 2018–2019, which affected the highest fire (hotspots, HSs) during the strong El Niño. Meanwhile, La Niña occurred three times in 2010–2011, 2011–2012, and 2017–2018, which is related to the low HSs found and represents the highest annual rainfall in the last ten years. The highest forest fire (HSs = 17.559) occurs in the characteristics of A1B4 (precipitation 0100, SSTA > 0.5C). The highest GHG emission (>400 Mton) occurred in 2015 when the strong El Niño occurred in South Sumatra Province. The strong and weak El Niño produces the highest GHG emissions of more than 30 Mton day^{-1}, while the maximum mean daily GHG emission is under 10 Mton day^{-1}. Hotspot numbers rise exponentially with increasing SSTA, showing strong statistical relationships ($R^2 > 0.80$, $r > 0.79$) with burned area ($R^2 = 0.90$, $r = 0.92$) and burned area with CO_2 emissions ($R^2 = 0.77$, $r = 0.79$).

Keywords: *forest fire, El Niño and La Niña, greenhouse gas emissions, precipitation, sea surface temperature anomaly*

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Introduction

Forest fires are the fourth biggest environmental problem in Indonesia after floods, waterspouts, and landslides. Over the last decades, over 5,030 forest fires occurred (>11% of all disasters), resulting in over 500 thousand fatalities and 183 damaged buildings (Badan Nasional Penanggulangan Bencana, 2024). The factors causing forest fires in Indonesia are commonly human activities sourced from social economy, etc., and supported by strong wind due to the large temperature difference between land and sea, El Niño, rainfall patterns, and land clearing (Andela & Werf, 2014; Hadiwijoyo, 2016; Iskandar et al., 2018; Hayasaka, 2023; Yulianti & Hayasaka, 2023). Forest fires cause environmental problems (smoke, haze), human health, societal problems, educational problems, economic problems, political problems, international relations problems, flora and fauna problems, and global climate change problems (Saharjo, 2022; Unik et al., 2024). Forest fires in Indonesia's peatland areas significantly impact the global economy (Hayasaka, 2023; Yulianti & Hayasaka, 2023).

La Niña and El Niño are prominent climate phenomena significantly impacting global weather patterns. El Niño is associated with high sea surface temperature when atmospheric convection zones on the tropical Pacific expand, and increased release of latent heat to the atmosphere drives the instability. La Niña is associated with low sea surface temperature near the equator with atmospheric convergence zones that are isolated from each other and permits the instability of trade winds and oceanic currents (Philander, 1985; Wang et al., 2019; Báez et al., 2022; Ramdzan et al., 2023; Li et al., 2023).

La Niña and El Niño have a significant impact on the climate and agriculture of South Sumatra Province. During La Niña, South Sumatra experiences heavy rainfall and cooler temperatures, increasing agricultural productivity. However, El Niño brings drought and scorching temperatures, leading to crop failures and water shortages (Anderson et al., 2023). These extreme weather patterns disrupt the province's economy, as agriculture is an important source of income for many residents (Bozzola et al., 2023). In addition, the increased frequency and intensity of wildfires during El Niño exacerbate the region's already severe air pollution, posing health risks to the local population (Singh & Zhu, 2021; Arrizaga et al., 2023; Masri et al., 2023). South Sumatra Province consists of a 20%

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peatland area in Sumatra Island (Hayasaka, 2023) with characteristics that significantly increase hotspots in strong El Niño phenomena (Burton et al., 2020; Nurdiati et al., 2021).

Forest fires increase greenhouse gas (GHG) emissions because they release carbon. GHG emissions are also affected by deforestation, land use change from forest to non-forest area, and land reclamation. The land use change in the peatland area is caused by increasing global palm oil demand and other land uses such as aquaculture and oil palm plantations (Basyuni et al., 2015; Saharjo, 2022). The high uncertainty in GHG emissions may be caused by large spatial heterogeneity (Hayasaka, 2023).

The forest fire's impact on GHG during the La Niña and El Niño periods is important to investigate in the South Sumatra Province. Forest fires occur frequently and release significant amounts of carbon dioxide and other GHGs into the atmosphere. Understanding how these emissions contribute to climate change and the intensification of extreme weather events is crucial to developing effective strategies to mitigate the effects of forest fires. In addition, research into the role of forest fires in GHG emissions can help policymakers and other stakeholders implement sustainable forest management practices and prevent future forest fire outbreaks (Singh, 2022; Liu & Shi, 2023).

This study aims to investigate the impact of forest fires on GHG emissions during extreme climate in the Southern Sumatra Province from 2010 to 2020. This research analyzes the effects of La Niña and El Niño on the region by analyzing factors such as precipitation patterns, temperature fluctuations, hotspots (Hss), and GHG emissions. This study is useful for understanding the complex relationship between forest fires and their contribution to the ever-evolving climate change phenomenon. This information can be used to develop strategies to reduce the frequency and impact of forest fires, ultimately reducing GHG emissions.

Methods

Research location This research was conducted in South Sumatra Province, Indonesia. The South Sumatera Province has a land area of 91,592.43 km² in the south of Sumatra Island. Sumatra Island is the world's sixth-largest island, covering 20% peatland (1.2 Mha) from South Sumatra Province. The South Sumatra Province is one of Indonesia's most prone to forest fires. The province also has extensive peatlands, which are highly flammable and increase the risk of forest fire. Some factors that caused forest fires in South Sumatra Province include land clearing by farmers, slash-and-burn agriculture, and a dry environment. The research site is presented in Figure 1.

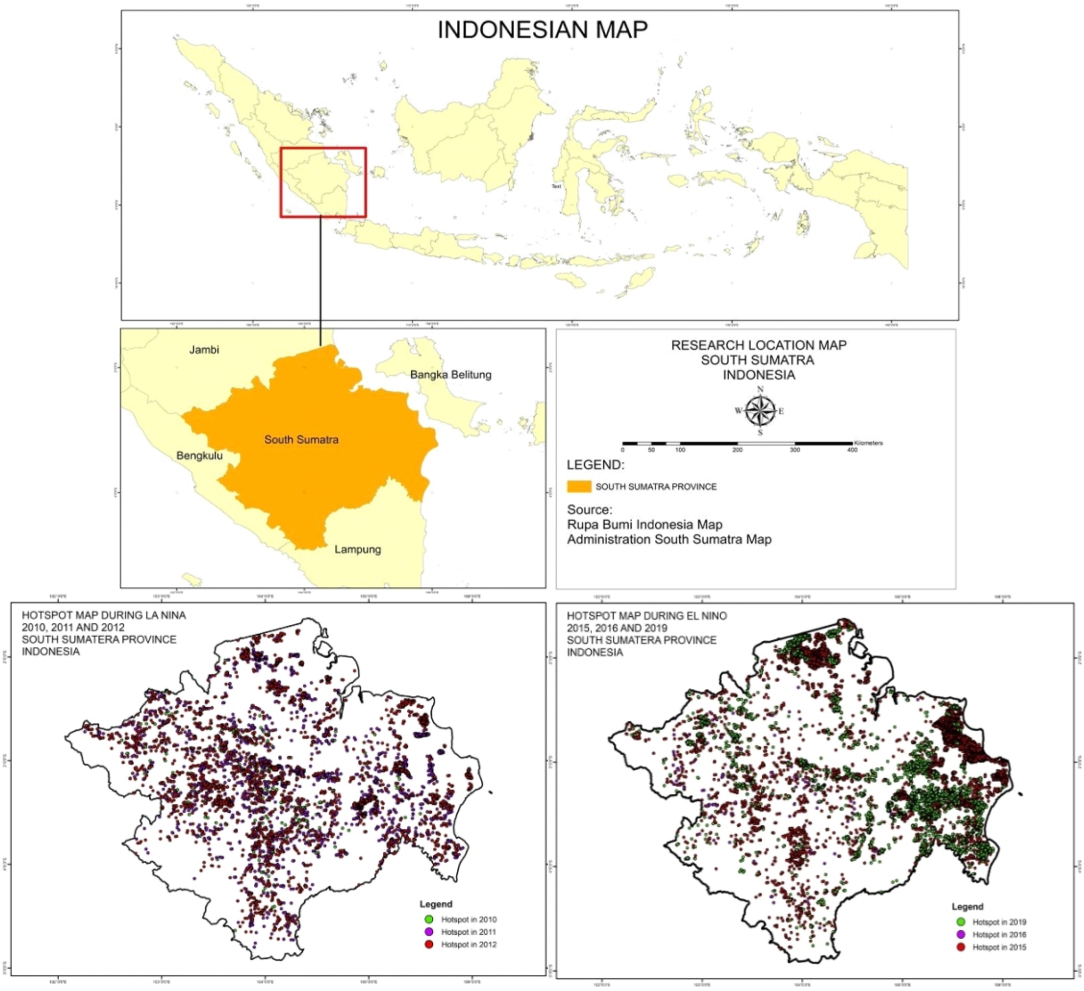

Figure 1 Research site.

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Research design and approach The research design of this study includes collecting fire hotspots and weather data from 2010 to 2020. The HSs and weather data for 10 years are then compared with the GHG emission data from 2010 to 2020. Based on the daily HSs, rainfall, and GHG data, we analyzed the climate change conditions, especially El Niño and La Niña events, about forest fire occurrence and GHG emission.

Data collection The monthly rainfall data for ten years, from 2010 to 2020, were obtained from the National Meteorology, Climatology, and Geophysical Agency for South Sumatra Province (*Badan Meteorologi, Klimatologi, dan Geofisika,* BMKG). The BMKG data are generated from daily rainfall data collected from the climatology station.

The HSs data for ten years, from 2010 to 2020, were detected from the Moderate Imaging Resolution Spectroradiometer (MODIS) on the Terra and Aqua satellites. The MODIS data were obtained from the National Aeronautics and Space Administration (NASA) Fire Information for Resource Management System (FIRMS) (https://firms.modaps.eosdis.nasa.gov/download). The spatial resolution of MODIS data from the Terra and Aqua satellites is approximately 1 km, with a temporal resolution of four daily observations when combining data from both satellites. HSs data have an accuracy value of more than 80% used to predict the occurrence of forest fires (Ardiansyah et al., 2017). The HSs data were used to evaluate the wildfires (forest fires) and identify the fire season, active fire period, and dates of major HSs peaks during the El Niño and La Niña periods.

The Nino 3.4 index for ten years from 2010 to 2020 was obtained from the National Oceanic and Atmospheric Administration (NOAA) (https://www.cpc.ncep.noaa.gov/data/indices/). This data provided information on the sea surface temperature anomaly (SSTA), an important indicator of these climatic phenomena, and identified El Niño and La Niña occurrences.

GHG emissions from 2010 to 2020 were obtained from Copernicus Atmosphere Monitoring Service (CAMS), Copernicus Climate Change Service (C3S) (https://climate.copernicus.eu/greenhouse-gases), and the national forest and land fire monitoring system (Sipongi+, https://sipongi.menlhk.go.id/). The data were collected from ground-based instruments, airborne measurements, and satellite data.

Burned areas from 2010 to 2020 were obtained from the National Forest and Land Fire Monitoring System (Sipongi+, https://sipongi.menlhk.go.id/). Sipongi+ originates from the Ministry of Environment and Forestry (MoEF) of the Republic of Indonesia, specifically under the Directorate of Forest and Land Fire Control.

Data analysis Monthly rainfall data (2010–2020) were analyzed as average monthly rainfall data during ten years to identify the dry season and rainy season in South Sumatra Province. The rainfall pattern was also used to explain the climate condition by comparing it with the Nino 3.4 index (SSTA).

The hotspot (HS) data is used to identify wildfires in South Sumatra. The HS data were analyzed to explain forest fire activities, annual fire history, fire-prone areas, and the fire season. The HS data were also used to explain the climate condition by comparing it with the Nino 3.4 index (SSTA).

The monthly rainfall and HS data were then analyzed with the Niño 3.4 index (SSTA) to explain forest fire characteristics in different climate conditions and clarify the El Niño and La Niña effects on forest fires in South Sumatra. El Niño and La Niña events were defined based on the NOAA threshold, where the Niño 3.4 SSTA exceeds +0.5°C for El Niño and falls below -0.5°C for La Niña, sustained for at least five consecutive overlapping 3-month seasons (Hashemi, 2021; NOAA Climate Prediction Center, 2023).

The GHG emission and burned area data clarify the effect of forest fires on GHG emissions from 2010 to 2020. This analysis is important for assessing the impact of climate change and planning mitigation and adaptation activities in forest fire-prone areas.

The regression and correlation analyses were conducted to examine the relationship between the number of HSs, SSTA at Niño 3.4, burned area, and wildfire CO (GHG) emissions in South Sumatra from 2010 to 2020. Pearson correlation coefficients were calculated using Microsoft Excel to assess the strength and direction of linear associations among these variables. Regression models were applied to visualize and quantify the effect of SSTA on the number of hotspots, as well as the cascading relationships from HSs to burned area and GHG emissions. The goodness-of-fit of the regression models was evaluated using the coefficient of determination (R^2). Additionally, graphical analysis and temporal trend comparisons were conducted to interpret the patterns across different phases. ArcGIS 10.5 was utilized primarily for visualizing the spatial distribution of HSs in South Sumatra. The software was used to generate thematic maps that depict the density and geographic spread of fire occurrences, which supported the interpretation of temporal and spatial trends in hotspot activity during El Niño and La Niña periods.

Results

Annual rainfall and fires The average monthly rainfall data from 2010 to 2020 ranges from 74.4 mm month^{-1} (July) to 387.5 mm month^{-1} (March). Based on the average monthly rainfall pattern, the dry months consist of May to October, and the wet months consist of November to April. The average monthly rainfall from 2010 to 2020 is presented in Figure 2.

Based on rainfall data from 2010 to 2020, the South Sumatra Province's rainfall pattern is included in zone A. The province falls within Zone A, with maximum rainfall in December, January, and February and minimum rain in July, August, and September (Aldrian & Susanto, 2003). These rainfall patterns indicate significant variation in South Sumatra Province's annual precipitation (Yates et al., 2023), which is commonly a characteristic of a tropical monsoon climate with distinct wet and dry seasons.

The heavy rainfall during December, January, and February provides ample water for agricultural activities and replenishes the region's water resources. Farmers in South Sumatra rely heavily on this seasonal rainfall to cultivate crops such as rice, coffee, and palm oil (Patel et al., 2023).

The dry season poses challenges for farmers as they have

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to manage water resources efficiently and employ irrigation systems to sustain their crops. The decrease in rainfall during dry months affects the overall climate of the region, leading to increased temperatures and decreased humidity (Asamoah et al., 2023). This can result in drought conditions and potentially increase the HSs in South Sumatra.

The annual rainfall and dry season rainfall in South Sumatra Province in the bottom part and the annual mean SSTA in Niño 3.4 in the upper part are presented in Figure 3a. The annual HSs in South Sumatra Province in the bottom part and the dry season SSTA in Niño 3.4 in the upper part are presented in Figure 3b.

South Sumatra Province has had annual rainfall in 10 years (2010–2020) ranging from 1,651 mm year^{-1} (2014) to 3,714 mm year^{-1} (2010). There have been four years (2010, 2012, 2013, and 2016) in which the annual rainfall exceeded the average annual rainfall during the ten years. Moreover, in 2011, 2014, 2015, 2018, and 2019, the annual dry season rainfall was under the average annual dry season rainfall (Figure 3a). Figure 3b shows the fire history based on HSs data from 2010 to 2020. The fire mostly happens in the dry season (May–October). The largest fire occurred in 2015 at about 15,316 HSs, followed by 2014 (4,532 HSs) and 2019 (4,029 HSs).

Extreme climate events impacted nearly all countries in 2015 and 2019. The prolonged dry season is the cause of the increase in HSs of South Sumatra. The highest forest fires happen on low precipitation (Guo et al., 2023). During the dry season, dry vegetation and high winds foster rapid fire spread (Planas et al., 2023). Hotspots indicate forest fires triggered by human activities such as land clearing and illegal logging.

Forest fires impact biodiversity loss, habitat devastation, increased air pollution, and health dangers (Ribeiro et al., 2023). Smoke and pollution produced by forest fires can spread and affect air quality in South Sumatra, other provinces, and even other countries.

La Niña and El Niño's effect on forest fires The Niño 3.4 index overviews the El Niño and La Niña phenomena based on the SSTA. Figure 4 presents a graph of (a) monthly SSTA and (b) consecutive overlapping 3-month seasons SSTA from 2010 to 2020 in South Sumatra Province. If there are more than or equal to 5 consecutive overlapping 3-month seasons of SSTA where the Niño 3.4 SSTA remains above +0.5 °C (El Niño) or below -0.5 °C (La Niña). The classification of weak, moderate, and strong El Niño or La Niña events is based on the peak value of consecutive overlapping 3-month seasons of SSTA (Figure 4b).

Figure 4a presents the monthly SSTA from 2010 to 2020, illustrating the temporal variability associated with El Niño and La Niña events. Positive anomalies, indicated by bars above zero, reflect warmer-than-average sea surface temperatures, which, if exceeding +0.5 °C for at least five consecutive overlapping 3-month seasons, are indicative of El Niño conditions. Conversely, negative anomalies, represented by bars below zero, signal cooler-than-average conditions associated with La Niña when values fall below –0.5 °C for a sustained period. The chart clearly highlights positive anomalies surpassing +2.5 °C in 2015 and negative anomalies around 2010–2011 approaching –1.5 °C. This temporal pattern demonstrates the cyclical nature of El Niño–Southern Oscillation (ENSO) phases and their potential climatic influence over time.

Over the decade spanning from 2010 to 2020, the SSTA exhibited significant interannual variability, characterized by fluctuations above and below the climatological average. A dominant cooling phase was observed in the early part of the decade, particularly during 2010–2011, followed by relatively neutral conditions in 2012 and 2013. A warming trend began to emerge in mid-2014 and peaked in 2015, with anomaly values exceeding +2.5 °C, indicating the occurrence of a strong El Niño event. This was followed by a sharp decline in SSTA during 2016 and alternating periods of weak

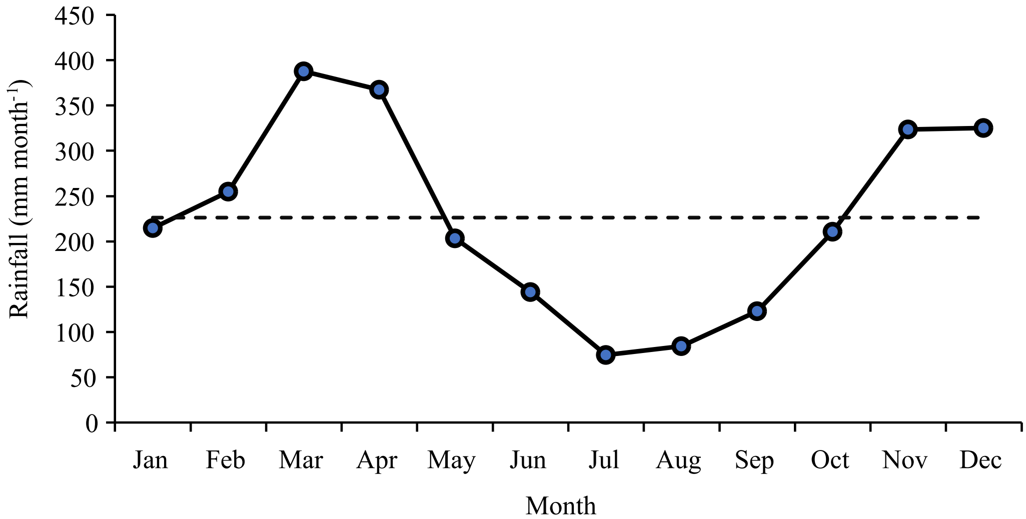

Figure 2 The monthly rainfall average.

warming and cooling in the subsequent years. By the end of 2020, a substantial decrease in SSTA signalled the onset of La Niña. These patterns reflect the complex dynamics of ocean-atmosphere interactions in the equatorial Pacific, which directly and indirectly influence regional climate conditions, including rainfall distribution, extreme temperatures, and drought severity across various regions.

Figure 4b presents the temporal pattern of Niño 3.4 SSTA from 2010 to 2020. The cooling episode occurred between mid-2010 and early 2011, with SSTA values falling below −1.5 °C, indicative of a strong La Niña event. This was succeeded by moderate La Niña conditions in late 2011, while the 2012–2013 period remained largely within the neutral threshold. Beginning in mid-2014, a progressive warming trend emerged, intensifying throughout 2015 and culminating in late 2015 with SSTA exceeding +2.5 °C, signaling a strong El Niño event. This phase coincided with severe hydroclimatic anomalies in Indonesia, including reduced precipitation and extended drought conditions, which significantly elevated forest fire risks in fire-prone areas such as South Sumatra. Following this, 2016 experienced a rapid transition into a cooling phase, returning to near-neutral and slightly negative anomalies. A weak La Niña developed in late 2017 and early 2018, followed by a weak El Niño at the end of 2018. Toward the end of 2020, the SSTA again dropped below −1.5 °C. These alternating episodes of warming and cooling reflect the dynamic ocean-atmosphere feedback mechanisms that drive climatic variability in the Indo-Pacific region. The relationship between forest fires (HSs), monthly precipitation, and SSTA from the Niño 3.4 index is presented in Figure 5.

The highest forest fire (HSs = 17,559) occurs in the characteristics of A1-B4 (precipitation 0100, SSTA > 0.5 °C), followed by A1B3 (HSs = 7,688) and A1B1 (HSs = 2,801). The highest forest fire occurs in August–October in the dry season (Figure 2 and Figure 5). The characteristics of HSs explain that the highest forest fire is also affected by the low monthly precipitation, and SSTA > 0.5 °C indicates the highest different SSTA as a sign of the El Niño arrival. The relationship between HSs and SSTA in September and October is presented in Figure 6.

September is the month when the most hotspots are found in South Sumatra (Hayasaka, 2023), followed by October. The statistical validation shows the number of HSs increases exponentially with rising SSTA values (Figure 6) and has high R^2 values (> 0.80) and the Pearson correlation (r) >79%. In both months, increasing positive SSTA values indicative of warming conditions in the equatorial Pacific correspond with a sharp rise in hotspot occurrences, reflecting heightened forest and land fire activity. The year 2015, marked by a strong warming phase with SSTA exceeding +2.5 °C, recorded the highest number of hotspots (over 7,000), highlighting the critical role of extreme ocean warming in exacerbating fire activity. While low or negative SSTA (e.g., 2010, 2011, 2016, 2020) is associated with relatively few hotspots, even moderate warming (around +0.5 °C) begins to show a marked increase in fire frequency.

Understanding seasonal trends in El Niño and La Niña events is important to anticipate and mitigate potential natural disasters. The relationship between forest fires and El Niño shows that forest fires increase due to extreme climatic conditions (Yin et al., 2020; de Oliveira et al., 2023). The

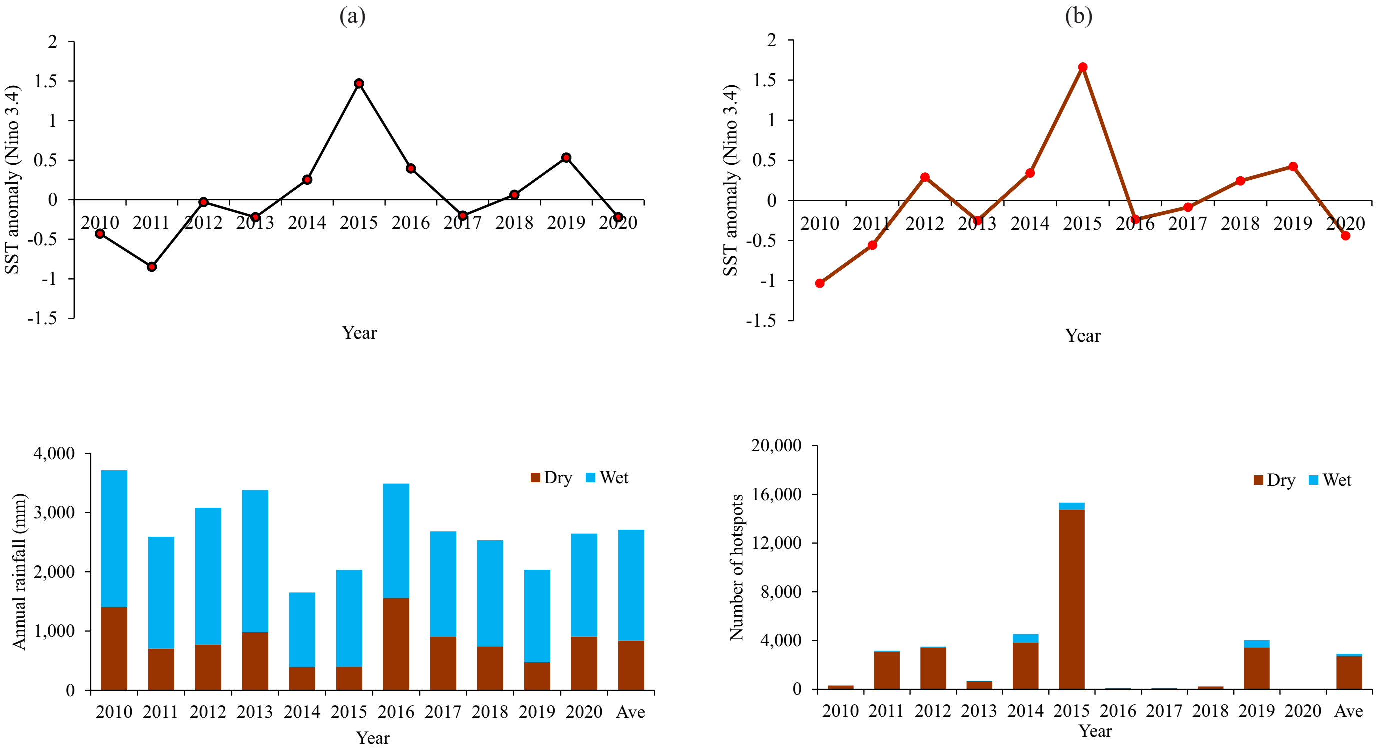

Figure 3 (a) annual rainfall and dry season rainfall in South Sumatra (bar graph) and annual mean SSTA in Niño 3.4 (line graph); (b) annual hotspots (HSs) in South Sumatra (bar graph) and dry season SSTA in Niño 3.4 (line graph).

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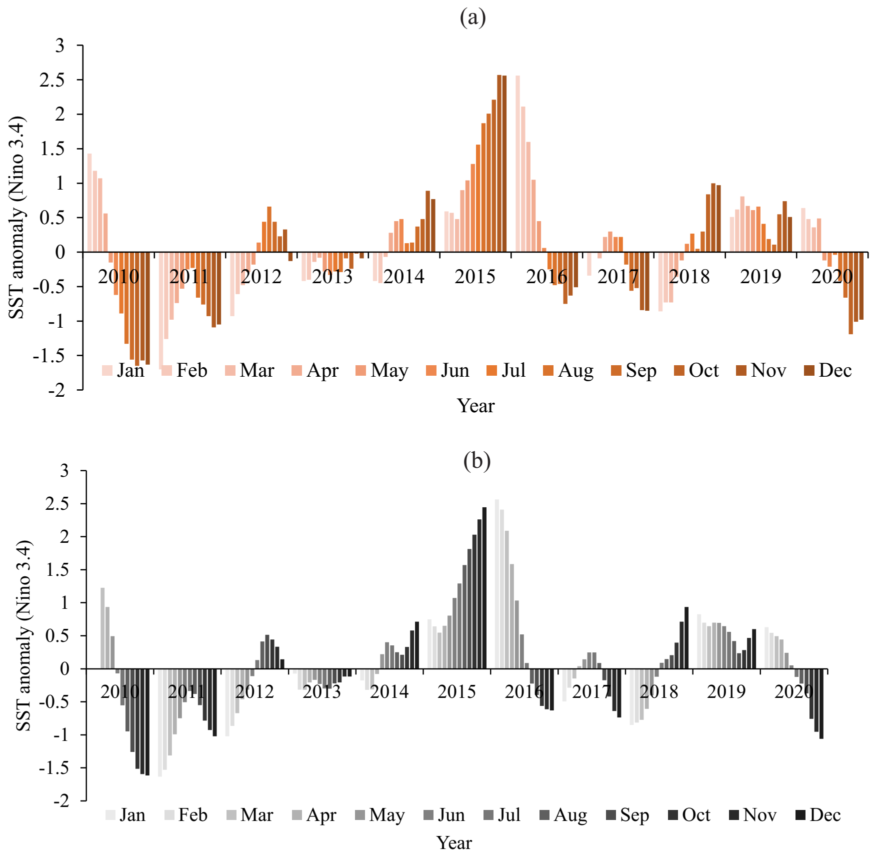

Figure 4 (a) monthly SSTA; (b) consecutive overlapping 3-month seasons SSTA from 2010 to 2020 in South Sumatra Province.

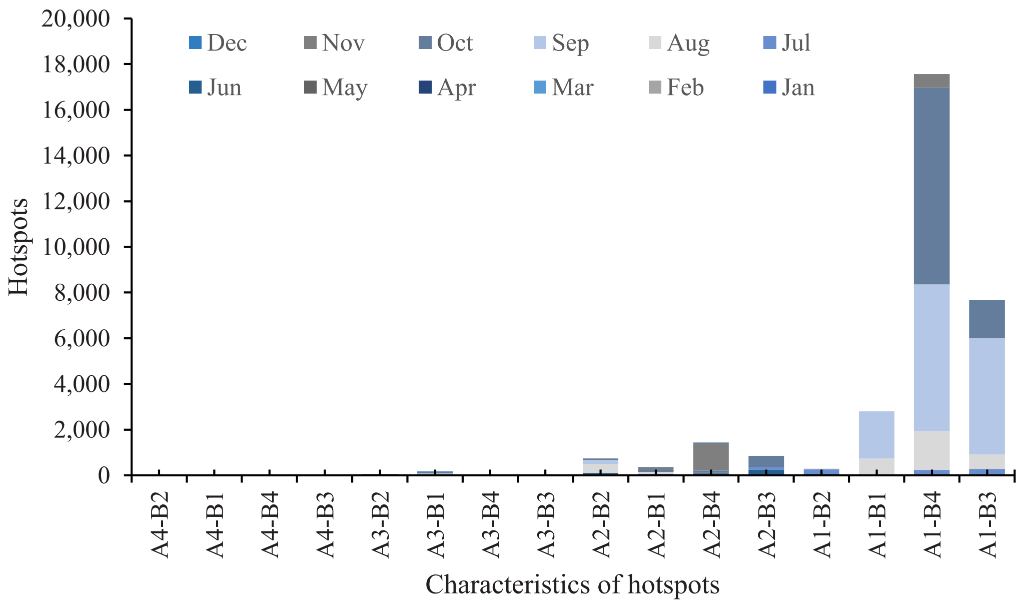

Figure 5 Characteristics of hotspots monthly precipitation based and SSTA.

Description*
A1-B1: Precipitation 0–100; SSTA < -0.5 C
A1-B2: Precipitation 0–100; SSTA -0.50 C
A1-B3: Precipitation 0–100; SSTA 00.5 C
A1-B4: Precipitation 0–100; SSTA > 0.5 C
A2-B1: Precipitation 100–300; SSTA < -0.5 C
A2-B2: Precipitation 100–300; SSTA -0.50 C
A2-B3: Precipitation 100–300; SSTA 00.5 C
A2-B4: Precipitation 100–300 SSTA > 0.5 C
A3-B1: Precipitation 300–500; SSTA < -0.5 C
A3-B2: Precipitation 300–500; SSTA -0.50 C
A3-B3: Precipitation 300–500; SSTA 00.5 C
A3-B4: Precipitation 300–500; SSTA > 0.5 C
A4-B1: Precipitation > 500; SSTA < -0.5 C
A4-B2: Precipitation > 500; SSTA -0.50 C
A4-B3: Precipitation > 500; SSTA 00.5 C
A4-B4: Precipitation > 500; SSTA > 0.5 C

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warmer and drier conditions associated with El Niño can create the perfect environment for fires to spread and become more intense. This is because increased heat and reduced rainfall make vegetation more susceptible to fire and make it difficult to control fire spread. The incidence of forest fires in South Sumatra Province is very high when the Niño 3.4 index exceeds 0.5. Moreover, mitigating the effects of El Niño and addressing climate change are crucial steps in preventing and reducing the occurrence of devastating forest fires (Parks & Abatzoglou, 2020).

GHG from forest fires GHG from forest fires are explained by wildfire CO_2 emission data from 2010 to 2020, as presented in Figure 7. Figure 7a shows that the highest GHG emission (>400 Mton) occurred in 2015 when the strong El Niño occurred in South Sumatra in the last ten years (2010–2020). The strong El Niño is characterized by precipitation under 100 mm month^{-1} and SSTA exceeding 0.5, which produces very high GHG emissions. Meanwhile, when the weak El Niño occurred in 2019, the GHG emissions were about 75 Mton lower than in the years that there was no El Niño (2011, 2012, and 2014).

The differences between mean daily GHG emissions (2003–2008), weak El Niño (2019), and strong El Niño (2015) are presented in Figure 7b. The strong El Niño produces relatively higher GHG emissions than the weak El Niño and the mean daily GHG emission. The strong and weak El Niño produces the highest GHG emissions of more than 30 Mton day^{-1}, while the maximum of mean daily GHG emissions is under 10 Mton day^{-1}. Table 1 presents the number of HSs, burned areas, and associated wildfire CO_2 emissions in South Sumatra from 2010 to 2020.

Fire activity reflected by the number of HSs, wildfire CO_2 emissions, and burned area shows a strong link with El Niño and La Niña events. The year 2015, during a strong El Niño, recorded the most severe fire activity. In contrast, La Niña years such as 2010 to 2012 exhibited lower fire activity, as La Niña typically brings wetter conditions that help suppress fires. In 2019, despite weak El Niño conditions, a moderate number of HSs (4,029) and a large burned area (336,798 ha) were recorded, suggesting the influence of local factors such as land use change and peatland burning. In 2020, although only 19 HSs were detected, CO_2 emissions reached 80 Mton and 95,000 ha were burned, indicating that even a small

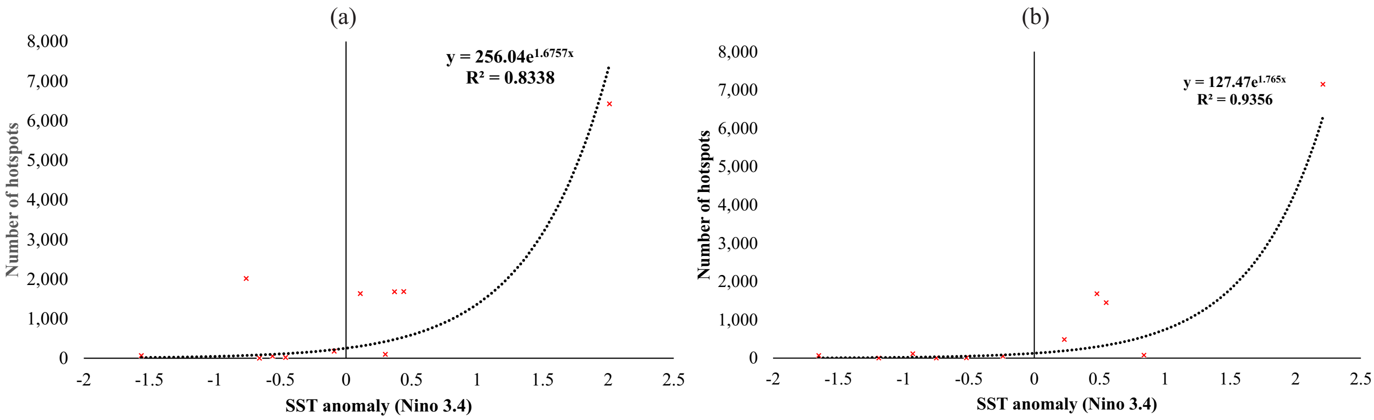

Figure 6 The relationship between HSs and SSTA in (a) September and (b) October.

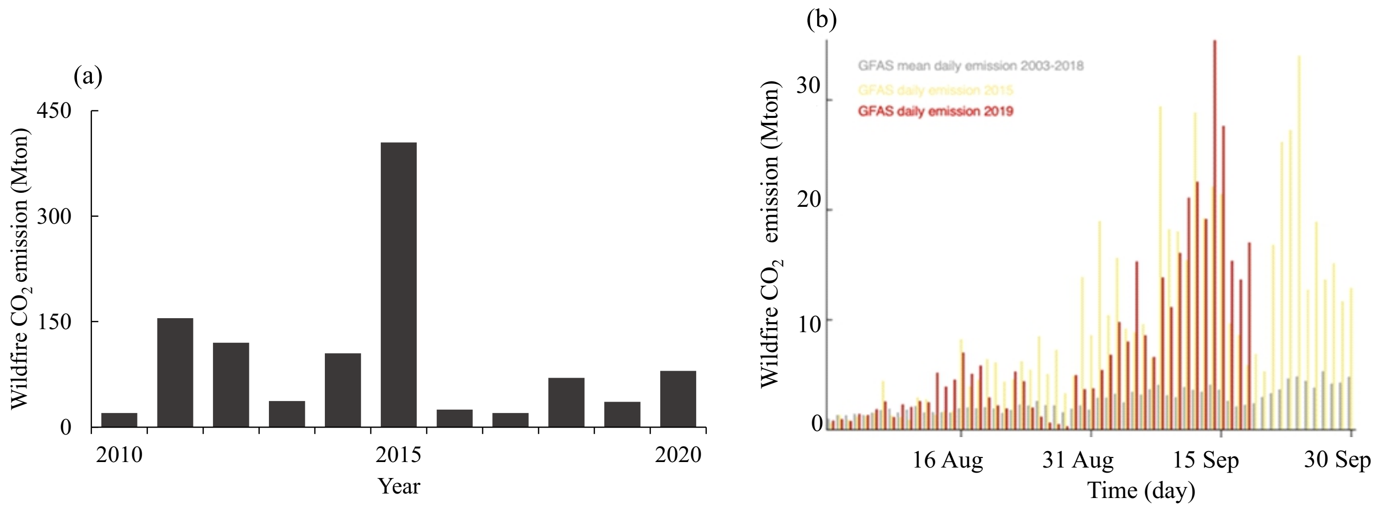

Figure 7 (a) wildfire CO_2 emissions from 2010 to 2020; (b) daily wildfire CO_2 emissions based on mean daily emissions (20032018), weak El Niño (2019), and strong El Niño (2015) (Source: Modified from Copernicus EU, 2019).

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number of undetected or smoldering fires, especially in peat areas, can contribute disproportionately to emissions. Overall, the data emphasize the combined influence of climate variability and local human activities on South Sumatra's fire dynamics. Figure 8 illustrates the graph of the cause and effect chain of more HSs causing a larger burned area effect to higher CO_2 emissions.

High R^2 values (exceeding 75%) in both graphs confirm that HSs are a reliable proxy for estimating burned areas and that burned area is a strong determinant of CO_2 emissions. As the number of HSs increases, the burned area expands non-linearly, suggesting that beyond a certain threshold, fire spread accelerates more rapidly. Larger burned areas tend to produce exponentially higher CO_2 emissions, likely due to the combustion of peatlands, which release vast amounts of carbon.

The statistical validation shows the number of HSs increases exponentially with rising SSTA values (Figure 6) and has high R^2 values (>0.80) and the Pearson correlation (r) >79%, indicating that Niño 3.4 anomalies can explain most of the variability in fire activity. Figure 8 clarifies the fire activity further and reinforces the validity of using HSs as a reliable fire activity indicator. HSs strongly correlate with burned area ($R^2 = 0.90$, $r = 0.92$), validating the use of hotspot data for fire extent estimation. Burned area correlates with CO_2 emissions ($R^2 = 0.77$, $r = 0.79$), confirming that larger fires release more GHG.

Discussion

Forest fires significantly impact GHG emissions and exacerbate climate change problems. When trees burn, they release large amounts of CO_2, into the atmosphere, contributing to the GHG effect and further warming the planet. The destruction of vegetation and the loss of carbon sinks in the form of trees further disrupt the balance of the carbon cycle in the ecosystem. Forest fires release carbon dioxide and have long-term consequences for the global climate. The increased forest fires can release other harmful GHGs, such as methane and nitrous oxide. These gases, along with carbon dioxide, can trap heat in the atmosphere and exacerbate the effects of climate change. However, the smoke and pollutants from forest fires can adversely affect humans and wildlife, causing respiratory problems and air pollution (Ravindiran et al., 2023).

The increasing incidence of wildfires is predominantly driven by rising global temperatures and shifting climatic patterns, which result in prolonged dry periods and an abundance of combustible material, thereby facilitating the rapid spread of fires. This issue is particularly pronounced in South Sumatra, where extensive peatland ecosystems,

Table 1 HSs, wildfire CO_2 emissions, and burned area in South Sumatra Province

Year	Number of hotspots (HSs)	Wildfire CO_2 emission (Mton)	Burned area (ha)
2010	306	20	5,422
2011	3,160	155	91.893
2012	3,487	120	193,145
2013	685	37	2,115
2014	4,532	105	401,469
2015	15,316	405	646,299
2016	107	25	8,785
2017	115	20	3,626
2018	239	70	16,227
2019	4,029	36	336,798
2020	19	80	95,000

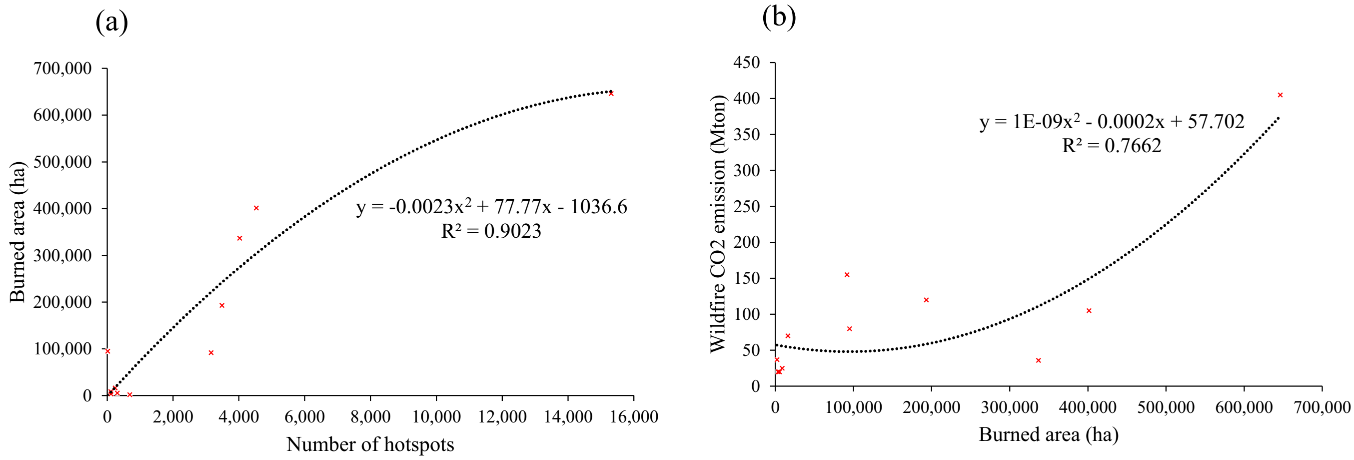

Figure 8 (a) the relationship between burned area and HSs; (b) the relationship between wildfire CO_2 emissions and burned area.

covering approximately 1.73 million ha, primarily concentrated in the Ogan Komering Ilir district, serve as a significant contributing factor to fire susceptibility (Muslikah & Yuliani, 2023). Peatlands, characterized by their high organic matter content, exhibit an inherent propensity for combustion, particularly under arid conditions (Putra et al., 2019). The susceptibility of these landscapes to fire is further exacerbated during the dry season, typically spanning from July to November, when monthly precipitation levels decline to below 100 mm, creating an environment highly conducive to fire ignition and propagation (Muslikah & Yuliani, 2023). Consequently, the prevalence of peatland fires in the region contributes substantially to GHG emissions, reinforcing a positive feedback loop wherein increased atmospheric carbon concentrations exacerbate climate change, which in turn intensifies the frequency and severity of wildfires. Addressing this escalating crisis necessitates a concerted global effort to implement sustainable land management practices, enhance early fire detection and suppression strategies, and develop comprehensive climate change mitigation policies to curb the adverse environmental and socio-economic impacts of recurring wildfires.

The combination of low precipitation during the dry season and increased GHG emissions from forest fires creates a vicious cycle (Zhong et al., 2023). Low precipitation leads to drier conditions, making the forests more susceptible to fires. As these fires release more GHG, they contribute to global warming, further drying the region. This continuous cycle of forest fires and reduced rainfall exacerbates the adverse effects of the climate, making it even more challenging for the affected communities to cope with the dry season.

This study explains the impact of forest fires on GHG emissions during the El Niño and La Niña periods in the last ten years (2010–2020) in South Sumatra Province. South Sumatra Province is a vulnerable forest fire area, especially during the dry season, because of the low precipitation, forest and peatland degradation, and anthropogenic activity. Moreover, investigating long-term trends and historical data will provide valuable insights into the cyclical nature of these climatic events and their effects on various ecosystems. Figure 9 illustrates the vicious cycle between climate change and forest fires, highlighting the interplay of climatic factors such as El Niño, La Niña, and SSTA, as well as forest and peatland degradation alongside anthropogenic drivers that collectively intensify fire risk and environmental degradation.

The escalation of forest fire occurrences in South Sumatra during El Niño events is influenced by extreme climatic anomalies, particularly prolonged drought and suppressed precipitation, which lead to a significant decline in soil and vegetation moisture content (Hayasaka, 2023). These hydrometeorological conditions increase landscape flammability, particularly in peat-dominated regions, as previously noted by Jessup et al. (2021), who emphasized the vulnerability of drained tropical peatlands to deep-seated fires. Our findings align with previous research that reported a strong positive correlation between SSTA in the Niño 3.4 region and fire activity across Indonesia (Hayasaka, 2023; Yuliyanti & Hayasaka, 2023), particularly during strong El Niño years such as 2015. In addition to climatic factors, anthropogenic drivers such as land-use conversion, deforestation, and slash-and-burn agriculture intensify fire risk (Hadiwijoyo, 2016; Jessup et al., 2021). Our study confirms these interactions, highlighting how El Niño-related climatic stress acts as a catalyst that amplifies the impact of human activities on fire occurrences.

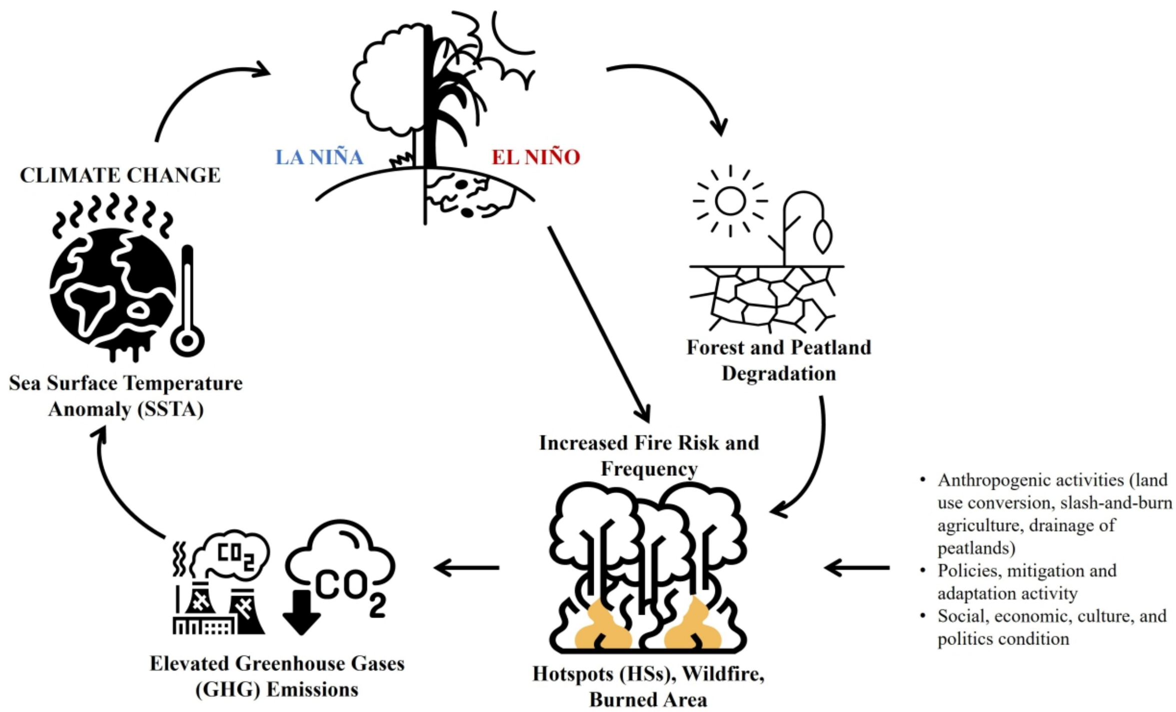

Figure 9 Vicious cycle diagram of climate change and forest fire.

In terms of governance response, Indonesia has enacted several national-level policies to mitigate fire risk, including Presidential Instruction Number 11/2015 on forest and land fire prevention, and the establishment of the Peatland and Mangrove Restoration Agency (*Badan Restorasi Gambut dan Mangrove*, BRGM) to address peatland degradation. These efforts were further supported by Ministerial Regulation Number P.32/MenLHK/Setjen/Kum.1/3/2016 concerning forest and land fire control. At the provincial level, South Sumatra has regulation Number 11/2015 and Number 8/2016 on forest and land fire control. Indonesia also has Sipongi+ as a forest and land fire information system, hotspot real-time monitoring, fire incident reporting with BMKG, and an early warning system. However, despite the presence of such policies, challenges remain in implementation and coordination, particularly at the local level. Inconsistent law enforcement, limited community engagement, and a lack of incentives for sustainable land management have limited the effectiveness of these interventions. Thus, our findings suggest that integrating climatic predictions with improved policy enforcement and locally tailored land governance strategies is essential to reduce the frequency and severity of fire events in South Sumatra.

Although this study offers important insights into the relationship between the ENSO and forest fire dynamics in South Sumatra, several methodological limitations should be acknowledged to ensure a comprehensive scientific appraisal. First, the analysis relies entirely on secondary data sources without the application of formal validation procedures or quantitative uncertainty assessments. This reliance may introduce potential biases, particularly in areas lacking ground check validation or where satellite detection accuracy may be affected by cloud cover or sensor resolution limitations. Second, while correlation and regression analyses provide useful statistical associations, they do not account for confounding variables such as land-use change, socio-economic drivers, or policy interventions that may independently influence fire activity apart from climatic variability. Third, the use of seasonal or monthly averages in data aggregation may obscure short-term anomalies or extreme events that could significantly impact fire occurrence. Fourth, the study does not incorporate predictive modelling approaches or spatiotemporal simulations, which would enhance the capacity to forecast future fire risks under varying ENSO scenarios. Therefore, future research should strengthen the methodological framework by integrating validated multi-source data, addressing potential sources of uncertainty, and employing climate-based and anthropogenic modelling tools to improve the reliability and policy relevance of the findings.

Conclusion

South Sumatra Province has had annual rainfall in 10 years (20102020) ranging from 1,651 mm year^{-1} (2014) to 3,714 mm year^{-1} (2010). The fire mostly happens in the dry season (MayOctober). The largest fire occurred in 2015 at about 15,316 HSs, followed by 2014 (4,532 HSs) and 2019 (4,029 HSs). The Niño 3.4 index represents the SSTA value that indicated El Niño occurrence in 20152016 (strong El Niño) and 20182019 (weak El Niño), while La Niña occurred three times: 20102011 (strong La Niña), 20112012 (moderate La Niña), and 20172018 (weak La Niña). The highest forest fire (HSs = 17,559) occurs in the characteristics of A1B4 (precipitation 0100, SSTA > 0.5 °C). The highest forest fires occur between August and October in the dry season. The highest GHG emission (>400 Mton) occurred in 2015 when the strong El Niño occurred in South Sumatra. The strong and weak El Niño produces the highest GHG emissions of more than 30 Mton day^{-1}, while the maximum mean daily GHG emission is under 10 Mton day^{-1}. The statistical validation shows the number of HSs increases exponentially with rising SSTA values and has high R^2 values (>0.80) and the Pearson correlation (r) >79%, indicating that Niño 3.4 anomalies can explain most of the variability in fire activity. The reliable fire activity indicator HSs strongly correlates with burned area (R^2 = 0.90, r = 0.92), validating the use of hotspot data for fire extent estimation. Burned area correlates with CO emissions (R^2 = 0.77, r = 0.79), confirming that larger fires release more GHG.

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