Spatiotemporal patterns and drivers of wildfire CO_2 emissions in China from 2001 to 2022 ~~Global carbon emission accounting: national-level assessment of wildfire CO_2 emission—a case study of China~~

Xuehong Gong[1,2], Zeyu Liu[2,3], Jie Tian[2,3], Qiyuan Wang[2,3], Guohui Li[2,3], Zhisheng An[1,2], Yongming Han[2,3*]

[1] State Key Laboratory of Earth Surface Processes and Resource Ecology, Faculty of Geographical Science, Beijing Normal University, Beijing 100875, China
[2] State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an 710061, China
[3] National Observation and Research Station of Regional Ecological Environment Change and Comprehensive Management in the Guanzhong Plain, Xi'an 710061, China

Correspondence to: Yongming Han (yongming@ieecas.cn)

Abstract. Wildfires release large amounts of greenhouse gases into the atmosphere, exacerbating climate change and causing severe impacts on air quality and human health. ~~Including carbon dioxide (CO_2) emissions from wildfires in international assessments and national emission reduction responsibilities is crucial for global carbon reduction and environmental governance.~~ In this study, based on a bottom-up approach and using satellite data, combined with emission factor and aboveground biomass data for different vegetation cover types (forest, shrub, grassland, cropland), the dynamic changes in CO_2 emissions from wildfires in China from 2001 to 2022 were analyzed. The results showed that between 2001 and 2022, the total CO_2 emissions from wildfires in China were 937.7~~693.7~~ Tg (522.6-1516.0 Tg, 1 Tg = 10^{12} g), with an annual average of 42.6~~31.5~~ Tg (23.8-68.9 Tg). The CO_2 emissions from cropland and forest fires were relatively high, accounting for 46~~45~~% and 46~~32~~% of the total, respectively. The yearly variation in CO_2 emissions from forest and shrub fires showed a significant downward trend, while emissions from grassland fires remained relatively stable. In contrast, the CO_2 emissions from cropland fires showed an ~~clear~~ upward trend, primarily in Northeast China. Hotspot analysis and Geographically and Temporally Weighted Regression (GTWR) models revealed significant spatial heterogeneity in emissions across vegetation types. Persistent hotspots of shrub and forest fires were located in Southwest and South China, while Northeast China experienced sporadic but extreme fire events. The GTWR model for shrub fire CO_2 emissions exhibited the highest predictive performance (R^2 = 0.87) and climatic factors (particularly temperature and humidity) were the main influencing factors. Notably, the recent rise in cropland fire CO_2 emissions in Northeast China is closely linked to region-specific straw burning policies. The research results provide valuable references for atmospheric transport models, regional fire management, and national carbon accounting frameworks in the context of climate change. ~~High CO_2 emissions from wildfires were mainly concentrated in the eastern regions of Heilongjiang and Inner Mongolia Provinces in China, accounting for 44% of the total annual emissions.~~

Various factors such as daily cumulative sunshine hours (Spearman's correlation coefficient, forest: -0.41, shrub:0.25; p < 0.001) and the normalized difference vegetation index (NDVI; Spearman's correlation coefficient, forest: -0.35, shrub: 0.37; p < 0.001), influenced CO_2 emissions from forest and shrub fires. Moreover, temperature (Spearman's correlation coefficient, -0.45, p < 0.001) primarily affected CO_2 emissions from grassland fires. The CO_2 emissions from cropland fires negatively correlated with the gross domestic product (GDP) (Spearman's correlation coefficient, -0.52, p < 0.001) and population density (Spearman's correlation coefficient, -0.51, p < 0.001). China's policy management has been crucial in reducing CO_2 emissions from wildfires. By accurately assessing CO_2 emissions from wildfires, governments worldwide can better set CO_2 reduction targets, take corresponding measures, and contribute to the global response to climate change.

1 Introduction

To limit the global average surface temperature rise to 1.5 °C higher than preindustrial levels, carbon dioxide (CO_2) emissions must reach net zero by mid-century through various pathways (Rogelj et al., 2018). Globally, wildfires reduced carbon storage in vegetation by approximately 10% from 2001 to 2012 (Lasslop et al., 2020). This significantly impacted the concentration of CO_2 in the atmosphere (Langenfelds et al., 2002; Van van Der der Werf et al., 2004; Wotawa and Trainer, 2000). The global annual CO_2 emissions from wildfires are approximately 6.5 to 11 billion tons, accounting for approximately one-fifth of the global CO_2 emissions from fossil fuels (Van Der Werf et al., 2010). According to Global Wildfire Information System data compiled by Our World in Data (Our World in Data, 2025), global wildfire CO_2 emissions have increased since 2020, fluctuating between 5 and 7 Gt CO_2 per year (1 Gt = 10^{15} g), with record-high levels observed in 2021 and 2023. However, the role of wildfires as a critical factor in carbon sinkssequestration and /sources is often overlooked. To mitigate climate change and fully understand the carbon exchange mechanisms between terrestrial ecosystems and the atmosphere, it is essential to consider the impacts of wildfire CO_2 emissions on the Earth system (Chuvieco et al., 2019; Giglio et al., 2018; Kasischke et al., 1995; McGuire et al., 2001; Zhang et al., 2013).

The significant differences in global wildfire CO_2 emissions among countries highlight the complexity of wildfire CO_2 emissions. Extreme forest fires in several countries, such as Australia, Canada, and the United States, often release CO_2 that exceeds the cumulative CO_2 emissions of several years in the same region, significantly impacting the global climate and the environment. Boreal fires, which usually contribute 10% of global fire CO_2 emissions, accounted for 23% in 2021 (0.48 Gt C billion metric tons of carbon), marking the highest fraction since 2000 (Zhang et al., 2023). The unprecedented wildfires in Canada in 2023 released significant amounts of air pollutants and greenhouse gases into the atmosphere. Simulation results (Wang et al., 2023) have indicated that these wildfires emitted more than 1.300 Tg Gt CO_2 and 0.140 GtTg CO_2 equivalent of other greenhouse gases, including CH_4 and N_2O. The greenhouse gas emissions associated with wildfires exceeded twice the planned cumulative anthropogenic emissions reductions in Canada over a decade. Shiraishi et al. (2021) used a bottom-up approach to estimate CO_2 emissions from catastrophic fires in Australia between 2019 and 2020. The results showed that from March 2019 to February 2020, Australia's Australia's annual CO_2 emissions were estimated to be 806 ± 69.7 Tg (1 Tg = 10^{12}

65 g)Tg CO_2 year^{-1}, equivalent to 1.5 times its total greenhouse gas emissions (CO_2 equivalent) in 2017. Phillips et al. (2022) reported that by the middle of this century, wildfires in northern North America could lead to a cumulative net source of approximately 12 Gtbillion tons of CO_2, accounting for approximately 3% of the remaining global CO_2 emissions, which is closely related to the temperature targets of the Paris Agreement. In the context of climate change, wildfires are becoming more frequent, and CO_2 emissions from wildfires are often influenced by human intervention. Phillips et al. (2022) found that

70 increasing investment in fire management to avoid CO_2 emissions is equivalent to or lower than other mitigation strategies. Therefore, changes in fire management may impact global atmospheric CO_2 concentrations, and proactive management strategies effectively reduce CO_2 emissions (Kelly et al., 2013; Phillips et al., 2022; Van Wees et al., 2021). Despite the growing importance of wildfire CO_2 emissions in climate change, such emissions are often excluded from international climate frameworks, including national inventories under the United Nations Framework Convention on Climate Change (UNFCCC),

75 due to their classification as "natural disturbances" in the Intergovernmental Panel on Climate Change (IPCC) guidelines for Land-Use Change and Forestry (LULUCF) (IPCC, 2019). However, CO_2 emissions from wildfires are not included in international assessments or national emission reduction responsibilities. Including wildfire CO_2 emissions in international assessments and national emission reduction responsibilities is crucial for global carbon reduction and environmental governance.

80   China has released numerous a large amount of wildfire emission inventory, but previous research on wildfire emissions in China has focused chiefly on small-scale regions and short-term periods (Cao et al., 2005; Huang et al., 2012; Qiu et al., 2016; Tian et al., 2011; Wu et al., 2018). Wang and Zhaoet al. (2008) established an atmospheric pollutant emission inventory of cropland fires in China in 2006 using the emission factor method and analyzed its spatiotemporal distribution characteristics. Wu et al. (2018) estimated pollutant emission inventories from wildfires in central and eastern China from 2003 to 2015 using

85 remote sensing images but did not include the heavily polluted northeast region. In addition, most studies have focused mainly on atmospheric pollutant emissions, with limited research on CO_2 emissions (Jin et al., 2022; Wang et aland Zhao., 2008; Xie et al., 2024; Yin et al., 2019). Xie et al. (2024) used the GEOS-Chem model to investigate the impact of cropland fires on severe haze events in Heilongjiang Province. They reported high uncertainty in the existing Global Fire Emissions Database (GFED) version 4.1 emission inventory. Van Der der Werf et al. (2017) also noted substantial uncertainty in estimating wildfire

90 emissions in existing emission inventories. Consequently, there is a critical need to quantify the long-term dynamics of wildfire CO_2 emissions across diverse vegetation types.Therefore, more work must be done to explore the long-term dynamics of wildfire emissions.

    Traditionally, wildfire emission inventories using population or cropland area weights to allocate total emissions to grid cells have high uncertainties (Streets et al., 2003; Zhang et al., 2013). With the advancement of remote sensing technology,

95 recent studies have shifted to satellite-based estimation methods, using active fire detection or burned area datasets to improve spatial accuracy. Inventories such as GFED (Chen et al., 2023) and the NCAR Fire Inventory (FINN) (Wiedinmyer et al., 2011) rely on satellite-derived fire count data (e.g., active fire product MCD14 ML) or burned area products (e.g., MCD64A1) to infer the timing and location of fire emissions (Giglio et al., 2016, 2018). Although satellite remote sensing has greatly

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improved the spatial and temporal resolution of fire detection, several practical challenges remain. For example, cloud cover, satellite overpass intervals, fire intensity thresholds, and pixel resolution can result in the underdetection of short-duration or low-intensity fires. To mitigate these limitations, this study integrated multi-source satellite products to enhance the completeness of the fire signal. Additionally, many existing global inventories rely on globally aggregated vegetation data (such as global land cover, and biomass), which further introduces errors, especially in transition zones between cropland and natural vegetation (e.g., forest-agricultural mosaics), where misclassification may lead to overestimation or underestimation of fire emissions.

To overcome these shortcomings, this study integrated China's regionally validated vegetation cover datasets (Xu et al., 2018) multi-source burned area satellite products, and regionally derived biomass data (Hu et al., 2006; Su et al., 2016; Yin et al., 2023) to develop a 500-meter resolution wildfire CO_2 emission inventory for China (2001-2022). Additionally, we used spatially weighted regression models to explore the drivers of emission variability and analyzed the impacts of national fire management policies on CO_2 emissions. The findings provide insights into the role of governance in shaping fire emissions and offer useful references for future wildfire management strategies. This multi-year emission inventory can also be used in atmospheric transport models to support the development of effective global warming mitigation strategies. This study estimated the CO_2 emissions from wildfires, including forest, shrub, grassland, and cropland fires in China from 2001 to 2022. Also, it explored the factors that may affect the spatiotemporal changes in CO_2 emissions from wildfires. The study results can provide high spatial resolution and long-term wildfire CO_2 emission inventories, which can enhance the accuracy of models assessing the impacts of wildfires on air quality, climate, and human health. Furthermore, this study provides essential scientific support for air pollution control strategies and is a critical foundation for accurately evaluating CO_2 emission reduction targets in various countries.

2 Data and methods

2.1 Study area

China is located in the eastern part of the Eurasian continent on the west coast of the Pacific Ocean. It spans approximately 50 degrees of latitude (3-53 °N) from north to south and 60 degrees of longitude (73-135 °E) from east to west, with a land area of approximately 9.60×10^6 km^2. There are differences in the geographical distribution of cropland, grassland, shrubs, and forests in China. In this study, China was divided into seven subregions based on geographic and ecological characteristics: Northeast China (NE), North China (NC), Central-West China (CW), South China (SC), Southwest China (SW), Northwest China (NW), and the Tibetan Plateau (TP) (Fig. 1). Croplands are mainly located in the eastern plains and coastal areas, especially in NE such as Northeast (provinces such as Heilongjiang, Jilin, and Liaoning), and NC North (Hebei), and East (provinces such as Hebei, Henan, Shandong, and Jiangsu) China, where the terrain is flat and suitable for agriculture. Grasslands are mainly distributed across in the Inner Mongolia region (spanning NE and CW), the Xinjiang region of NW, and parts of SW. Forests and shrubs are primarily concentrated in NE (especially Heilongjiang), SW (provinces such as Yunnan,

Guizhou, and Sichuan), and SC (provinces like Jiangxi and Hunan). ~~North (such as Inner Mongolia and Xinjiang) and Southwest (such as the western Sichuan Plateau) of China, forming a vast grassland ecosystem. Shrubs are mainly distributed in mountainous and semiarid areas. Forests are mainly distributed in Northeast (Heilongjiang, Jilin, and Liaoning) and Southwest (Yunnan, Guizhou) China, which have abundant forest resources.~~

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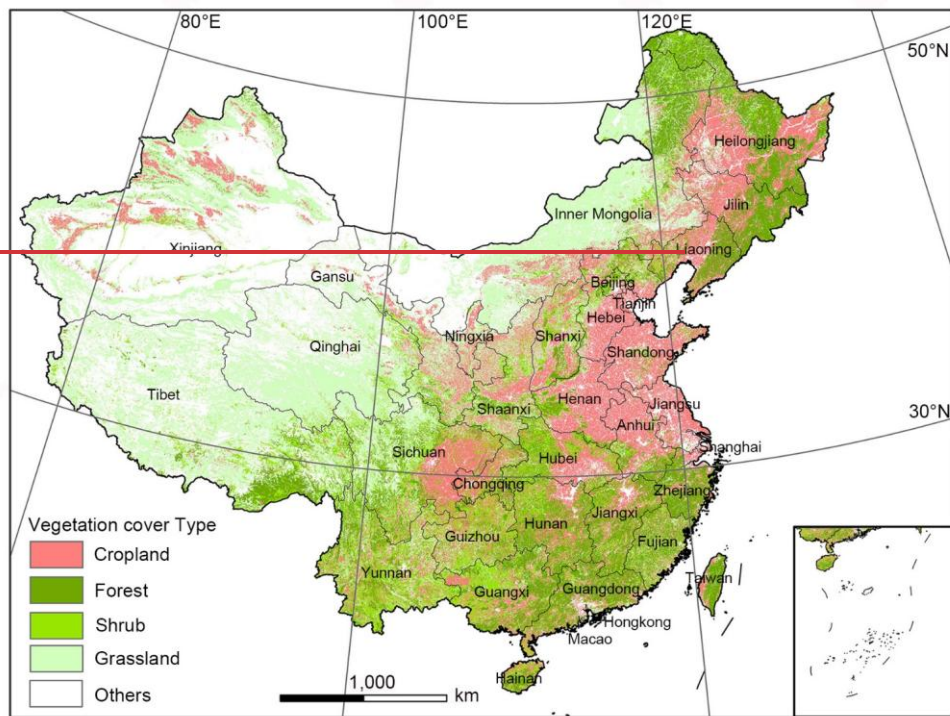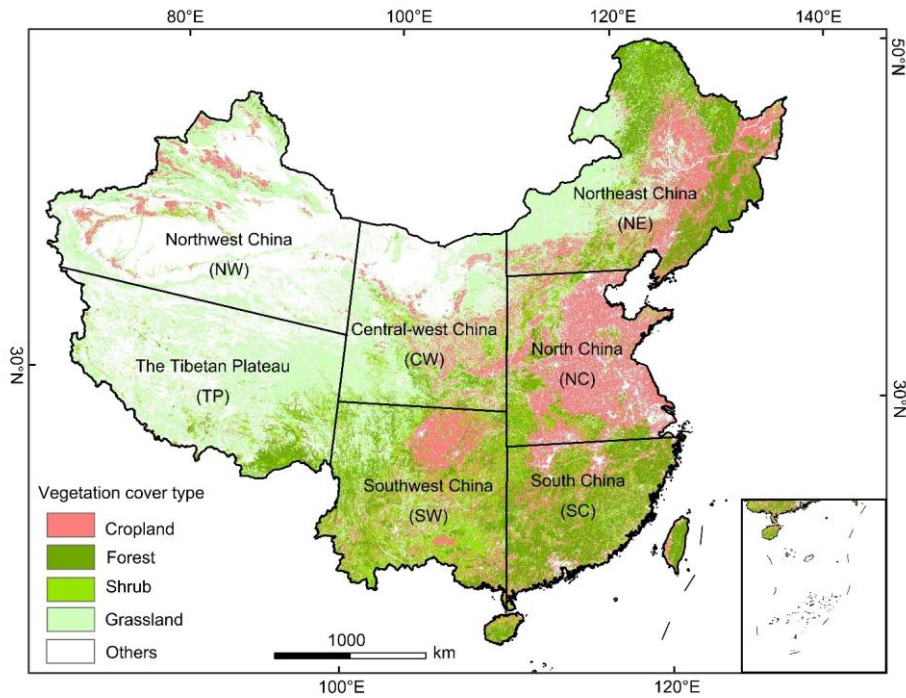
Figure 1: Regional divisions and vegetation distribution in China. The seven regions include: North China (NC): 109°E to eastern border, 30-41°N; South China (SC): 109°E to eastern border, south border to 30°N; Southwest China (SW): 100-109°E, south border to 32°N; Central-West China (CW): 100–109°E, 32°N to northern border; Northeast China (NE): 109°E to eastern border, 41°N to northern border; Northwest China (NW): Western border to 100°E, 36°N to northern border; the Tibetan Plateau (TP): Western border to 100°E, south border to 36°N.

2.2 Data

The burned area data for wildfires with a spatial resolution of 500 m were sourced from MODIS MCD64A1 burned area product (Giglio et al., 2018). The vegetation cover data were sourced from the China Land Use Land Cover Remote Sensing Monitoring Dataset (CNLUCC), with a spatial resolution of 30 m (Xu et al., 2018). A 1 km harvesting area dataset for three staple crops (e.g., corn, wheat, and rice) in China from 2000 to 2019 was obtained from Luo et al. (2020). Vegetation cover data were combined with fire area data to extract spatial data, including the time and geographic coordinates of fire occurrence, burned area, and vegetation cover types (corn, wheat, rice, grassland, shrub, and forest). The meteorological data were obtained from the Daily Meteorological Dataset of Essential Meteorological Elements of the China National Surface Weather Station

150 (V3.0), and the spatial distribution of the meteorological data was calculated using the Kriging interpolation method in the ArcGIS 10.8 environment. The vegetation cover fraction was sourced from China's regional 250 m fractional vegetation cover dataset (Gao et al., 2024a). The normalized difference vegetation index (NDVI) data were sourced from China's regional 250 m normalized difference vegetation index dataset (Gao et al., 2024b).

2.23 CO_2 emission estimationMethods

155   In this study, we employed a bottom-up approach to develop an inventory of China's wildfire CO_2 emissions. Wildfire CO_2 emissions were calculated using the following formula:

$$E_i = \sum_{x,i} BA_{x,i} \cdot \times \cdot AGB_{x,i} \cdot \times \cdot CE_i \cdot \times \cdot EF_i \qquad (1)$$

where the subscripts x and i represent the grid cell and vegetation cover type (forest, shrub, grassland and cropland), respectively. The vegetation cover data were sourced from the China Land Use Land Cover Remote Sensing Monitoring
160 Dataset (CNLUCC) (Xu et al., 2018). and a 1 km harvesting area dataset for three staple crops (e.g., corn, wheat, and rice) in China from 2000 to 2019 was obtained from Luo et al. (2020). E_i represents the CO_2 emissions, $BA_{x,i}$ is the burned areas (ha), $AGB_{x,i}$ is the aboveground biomass (t ha^{-1}), and EF_i is the emission factor. CE_i is the combustion efficiency. All datasets were resampled to 500 m resolution to ensure spatial consistency.

2.2.1 Burned areas

165   BA for each vegetation cover type was primarily estimated using the MODIS-MCD64A1 product (Giglio et al., 2018), which provides global monthly burned area estimates. However, it is well acknowledged that MODIS-MCD64A1 tended to underestimate small and fragmented fires. To address this issue, we applied scaling factors (α_i) to correct the MODIS-derived BA estimates. The scaling factors were derived from the comparison of MODIS-derived BA with two independent global burned area datasets: the FireCCI51 product (Lizundia-Loiola et al., 2020) released by ESA (http://cci.esa.int/data) and a global
170 GFED500 product (Van Wees et al., 2022), with their specific values provided in Table S1. The corrected burned area for each land cover type was obtained by multiplying the MODIS-derived BA values by the corresponding scaling factor. This correction accounts for the known systematic underestimation of small and fragmented fires by the MODIS MCD64A1 product.

$$BA_{\text{corrected},i} = BA_{\text{MODIS},i} \times \alpha_i \qquad (2)$$

where i denotes vegetation type.

2.2.2 Emission factors

175   The emission factor refers to the gas released pe

2.3.1 Emission factors

The emission factor refers to the gas released per unit mass of dry combustible material during combustion, typically in grams per kilogram (g kg^{-1}). This is a crucial parameter for calculating gas emissions during biomass burning, such as CO_2, methane (CH_4), and carbon monoxide (CO). Emission factors are influenced by various factors, including the combustibility of tree species, differences in vegetation cover types, and the intensity of flame combustion (Andreae and Merlet, 2001; Lü et al., 2006). To ensure the accuracy of the wildfire emission inventory as much as possible, it is essential to choose appropriate emission factors. This study comprehensively analyzed many studies in the literature to summarized the emission factors of CO_2 generated by wildfires under different vegetation cover types, as listed in Table S1S2. Finally, the average values from the literature were selected as the emission factors of the different vegetation cover types.

2.32.2 3 Aboveground biomass

Previous studies have mainly used the aboveground biomass data from Fang et al. (1996) for forests. Forest aboveground biomass data in recent years need to be updated. In this study, the aboveground biomass data of shrubs and forests from 2001 to 2012 were obtained from Su et al. (2016). The data for 2013 to 2022 were obtained from Yan et al. (2023). For shrub, Chinese local biomass density data were collected in Table S3 (Hu et al., 2006). Grassland aboveground biomass was calculated using the exponential model by Gao et al. (2012):

$$AGB_{grass} = 20.1921 \times e^{3.2154 \times (NDVI)} \tag{13}$$

where AGB_{grass} is the aboveground biomass of grassland (g m^{-2}) based on the average normalized difference vegetation index (NDVI) NDVI value of the growing season. The aboveground biomass of cropland was obtained by multiplying the crop-specific yield per unit area by the straw-to-product ratio. NDVI data were sourced from China's regional 250 m normalized difference vegetation index dataset (Gao et al., 2024b).

To determine the aboveground biomass of cropland, we gathered the crop-specific yield per unit area of different crops from the China Statistical Yearbook (NBSC, 2001-2022). The aboveground biomass burned in the field of cropland from major crops is calculated from the crop-specific yield per unit area, the straw production rates and the dry matter content of each crop residue as follows:

$$AGB_i = P_i \times R_i \times D_i \tag{4}$$

where i represented crop type (rice, corn, wheat and other crops), AGB_i was the aboveground biomass of cropland burned in the field (g m^{-2}); P_i was the crop-specific yield per unit area (g m^{-2}), R_i was the straw yield ratio for each crop type; D_i is the dry matter content of each crop residue. The other crops were defined as the average of rice, corn, and wheat. For each crop type, data for R and D were collected from published literature (Table S4).

The crop-specific yield per unit area (rice, corn, wheat) was derived from the China Statistical Yearbook, while the crop-specific yield per unit area of other crops was defined as the average of rice, corn, and wheat. The straw-to-product ratios for

2.2~~3.4~~3 Combustion efficiency

The combustion efficiency (CE) of biomass is a crucial factor determining the accuracy of wildfire CO_2 emissions estimates. It is influenced by multiple factors, including fire intensity, wildfire type, moisture content and load of combustibles, as well as meteorological conditions. Hély et al. (2003) established an empirical relationship between combustion efficiency and vegetation cover fraction (FVC), which was applied in this study to calculate the CE for forests and grasslands. The FVC used in this study was sourced from China's regional 250 m fractional vegetation cover dataset (Gao et al., 2024a). For regions with an FVC exceeding 60%, the CE values for forest and grassland were set at 0.3 and 0.9, respectively. When the FVC was below 40%, the CE values for forest and grassland were 0 and 0.98, respectively. In areas where the vegetation cover ranged from 40% to 60%, the CE for forest cover was defined as 0.3. The CE for grassland was calculated using the following formula:

$$CE = e^{-0.13 \times FVC} \tag{5}$$

The CE of shrub was set at 0.7, based on a China-specific literature and global biomass burning studies (Junpen et al., 2020; Mieville et al., 2010; Ping et al., 2021; Van Leeuwen et al., 2014; Zhou et al., 2017). The CE of corn, wheat, and rice was obtained from He et al. (2015), with values of 0.92, 0.92, and 0.93, respectively. The CE of other crops was taken as the average value for corn, wheat, and rice (i.e., 0.923).

It is important to note that although the CE values for different vegetation types were carefully selected based on comprehensive literature reviews, CE is inherently variable and can differ significantly across various combustion phases. Since this study aimed to estimate emissions over extended periods (ranging from months to years), the adopted CE values represent average combustion conditions rather than instantaneous ones. This averaging approach may introduce uncertainties in the emission estimates, especially in scenarios where rapid changes in combustion efficiency occur.

The combustion efficiency of biomass is an essential factor affecting the accuracy of wildfire CO_2 emission estimates. It is influenced by the intensity of fires, wildfire type, moisture content and load of combustibles, and meteorological conditions. Hély et al. (2003) established an empirical relationship between combustion efficiency and vegetation cover fraction (FVC). This relationship was applied in this study to the combustion efficiency calculation for forests, shrubs, and grasslands.

$$CF = \begin{cases} 0.98 & if\ 40\% \leq FVC\ for\ grassland \\ exp(-0.13 \times FVC) & if\ 40\% < FVC \leq 60\%\ for\ grassland \\ exp(-1.3 \times FVC) & if\ T_c \leq 60\%\ for\ forest\ and\ shrub \\ 0.25 & if\ FVC > 60\%\ for\ forest \\ 0.3 & if\ FVC > 60\%\ for\ shrub \\ 0.9 & if\ FVC > 60\%\ for\ grassland \end{cases} \tag{2}$$

where CF is the combustion efficiency, and FVC is the vegetation cover fraction. The combustion efficiencies of corn, wheat, and rice were obtained from Zhou et al. (2017), with values of 0.92, 0.92, and 0.93, respectively. The combustion efficiency of other crops was taken as the average value for corn, wheat, and rice (i.e., 0.923).

2.3.4 CO_2 emission estimation

Using a bottom-up approach to estimate China's wildfire CO_2 emissions inventory, the wildfire CO_2 emissions are calculated using the following formula for forest, shrubs, and grasslands:

$$E_t = \sum_{x,t} BA_{x,t} \times AGB_{x,t} \times CF_t \times EF_t \tag{3}$$

where the subscripts x and i represent the location and vegetation cover type, respectively. E_t represents the CO_2 emission, $BA_{x,t}$ is the burned area (ha), $AGB_{x,t}$ is the aboveground biomass (t ha^{-1}), and EF_t is the emission factor. CF_t is the combustion efficiency.

For cropland fires, cropland was further divided into four categories: rice, wheat, corn, and others. The specific calculation formula is as follows:

$$E_j = \sum_{x,j} \times EF_j \tag{4}$$

where the subscripts x and j represent the location and type of crop, respectively. E_j represents the CO_2 emissions, $BA_{x,j}$ is the burned area, $B_{x,j}$ is the per hectare yield of crop type j at location x, N_j is the straw-to-product ratio, EF_j is the emission factor, and CF_j is the combustion efficiency.

2.3 Spatiotemporal analysis of wildfire CO_2 emissions

2.3.1 Global spatial autocorrelation analysis

Global spatial autocorrelation is a fundamental concept in spatial statistics, used to assess the overall spatial dependence of a variable across a study region. Anselin's Moran's I index (Anselin, 1995; Moran, 1948) and the Getis-Ord Gi coefficient* (Getis and Ord, 1992) are commonly used to measure the degree of spatial clustering and heterogeneity. Moran's I is a global spatial autocorrelation statistic that quantifies the degree to which similar attribute values are clustered or dispersed in space. The Moran's I is calculated as follows:

$$I = \frac{n}{s_0} \times \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^{n}(x_i - \bar{x})^2} \tag{6}$$

where I is the Global Moran's I index, n is the total number of spatial elements; x_i and x_j are the observed values at spatial units i and j, respectively; $\bar{x}$ is the mean of all observed values; w_{ij} is the weight matrix for the adjacency relationships between geographical units; S_0 is the sum of all spatial weights.

The Moran's I is between -1 and 1. A value of I > 0 indicates positive spatial autocorrelation, i.e., similar values (high or low) tend to occur near each other, while I < 0 indicates dissimilar values are adjacent. I ≈ 0 suggests a random spatial pattern.

Statistical significance is assessed by comparing the observed Moran's I to a null distribution generated via random permutations. A z-score > 2.58 and p-value < 0.01 indicates a statistically significant spatial clustering pattern at the 99% confidence level. In the context of this study, significantly positive Moran's I values indicate that wildfire CO_2 emissions are spatially clustered, meaning that regions with high emissions tend to be adjacent to other high-emission areas, and low-emission regions are likewise grouped. This justifies further localized analyses such as hotspot detection.

2.3.2 Hot spot analysis

While Moran's I provides a global measure of spatial autocorrelation, it does not explicitly identify localized clusters of high or low values. To address this limitation, the Getis-Ord Gi* statistic (Getis and Ord, 1992) is commonly used to identify statistically significant hotspots and coldspots within spatial datasets. Unlike Moran's I, which captures both positive and negative spatial autocorrelation, the Gi* statistic focuses on detecting concentration patterns of high or low values within the study area. The Getis-Ord Gi* statistic is defined as:

$$G_i^* = \frac{\sum_j w_{ij} x_j - \bar{x} \sum_j w_{ij}}{S \sqrt{\left[\frac{n \sum_j w_{ij}^2 - (\sum_j w_{ij})^2}{n-1}\right]}} \tag{7}$$

Where G_i^* is the Getis-Ord Gi* statistic for location i; x_j is the observed value at location j (e.g., CO_2 emissions); $\bar{x}$ is the global mean of the observed variable; w_{ij} is the spatial weight matrix, representing the spatial relationship between locations i and j; n is the total number of spatial units; S is the standard deviation of the observed values.

The Gi* statistic is essentially a ratio that compares the local sum of a variable within a specified distance to the global sum, adjusted for the number of spatial units and their spatial relationships. High positive Gi* values indicate clusters of high values (hotspots), while low negative Gi* values indicate clusters of low values (coldspots). Locations with Gi* values near zero indicate random spatial patterns without significant clustering. Statistical significance is assessed using Z-scores and corresponding p-values. In this study, Gi* analysis was used to detect persistent high- and low-emission clusters of wildfire CO_2 emissions across China from 2001 to 2022. The results provided spatially explicit insights into emission patterns.

2.3.3 Geographically and temporally weighted regression model

To capture the spatial and temporal variations of the drivers of wildfire CO_2 emissions, the Geographically and Temporally Weighted Regression (GTWR) model was used (Huang et al., 2010). Unlike traditional global regression models, GTWR allows the coefficients of explanatory variables to vary across both space and time, providing a more precise estimation of the local influence of different driving factors. The GTWR model is defined as:

$$y_i = \beta_0(u_i, v_i, t_i) + \sum_k \beta_k(u_i, v_i, t_i) x_{ik} + \epsilon_i \tag{8}$$

Where x_i is the response variable (wildfire CO_2 emissions); (u_i, v_i, t_i) are the spatial coordinates and timestamp for location i; β_0 is the intercept term; β_k is the local coefficient for the kth explanatory variable; x_{ik} is the kth explanatory variable; ϵ_i is the error term. The accuracy of the GTWR model depends significantly on the choice of bandwidth and kernel

function, which control the spatial and temporal influence of neighboring observations. In this study, an adaptive bandwidth was used to ensure that each observation has a sufficient number of neighbors, while a tricube kernel was selected for its smooth distance decay function. The optimal bandwidth was determined using the corrected Akaike Information Criterion
300 (AICc), a widely used criterion for model selection that balances model complexity and goodness of fit (Hurvich et al., 1998; Hurvich and Tsai, 1989). This approach enabled us to explore how the effects of climatic and socioeconomic variables on wildfire emissions vary across regions and over time.

3 Results and discussion

3.1 Interannual ~~Variation~~ variation in CO_2 ~~Emissions~~emissions

305 The total CO_2 emissions from wildfires in China from 2001 to 2022 were 937.7 (522.6-1516.0 Tg)~~693.7~~ Tg, with an average annual value of 42.6 (23.8-68.9)~~31.5~~ Tg, ~~accounting for 0.46% of the total global emission of All fire types (GFED4, all fire types mean of 7140 Tg from 2001 to 2022, Van Der Werf et al., 2017), and 0.52% of China's fossil fuel emission (approximately 6400 Tg, Shan et al., 2017).~~ CO_2 emissions from wildfires in China were relatively low, decreasing slowly by 0.60~~0.43~~ Tg per year (Fig. 2a). CO_2 emissions from cropland and forest fires were relatively high, accounting for 45~~46~~% and
310 46~~32~~% of the total wildfire emissions in China, respectively; shrub fires emissions account for 8~~20~~% of the total wildfire emissions in China, while grassland fire emissions were the lowest, accounting for only 2% of the total wildfire emissions in China (Fig. 2b).

315 **Figure 2: (a) Annual CO$_2$ emissions within specific vegetation cover types from 2001 to 2022 in China; (b) Contribution of different vegetation cover types to the total CO$_2$ emissions from 2001 to 2022 in China. (c-f) Time series of CO$_2$ emissions for forest, shrub, grassland and cropland, respectively; the red dashed line is the linear trend and the grey shaded envelope represents the 5th-95th percentile confidence interval from Monte Carlo uncertainty analysis; the p-values are derived from the Mann-Kendall trend test, a non-parametric statistical method used to assess the presence of a monotonic (increasing or decreasing) trend in a time series**
320 **without assuming any specific data distribution. A p-value < 0.05 indicates a statistically significant trend at the 95% confidence level.**

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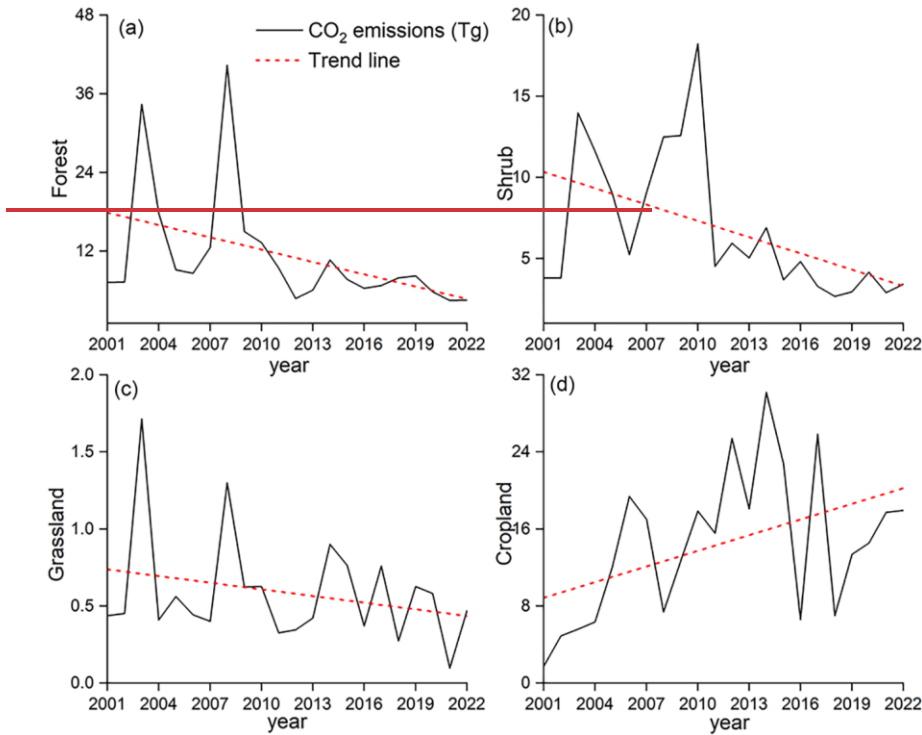
The annual CO$_2$ emissions from different types of fires showed varying temporal trends. The downward trend for forest and shrub emissions was significant, with a decrease of 1.10.63 and 0.233 Tg per year, respectively (Fig. 3a 2c and 3b2d). Such a decline may reflect effective forestry management strategies for forest and shrub fires (Fig. 12). In contrast, cropland
325 emissions showed a clear upward trend, with an annual increase of 0.63 Tg (Fig. 3e2f). This may be attributed to the increased

agricultural intensity and straw production in major grain-producing regions, particularly in northeastern China. Additionally, shifts in local open-field burning management strategies, such as the introduction of temporally concentrated burning windows, may have enhanced the detectability of agricultural fires via remote sensing. ~~This may be related to an increase in agricultural activities, changes in land use, or an increase in cultivation intensity.~~ The emission trend for grassland was relatively stable (Fig. ~~3d~~2e), which might be influenced by a combination of ecological and anthropogenic factors.

~~Figure 3: Time series of CO_2 emissions for different vegetation cover types from 2001 to 2022 in China: (a) Forest, (b) Shrub, (c) Grassland, (d) Cropland.~~

~~3~~3.2 Monthly ~~Variation~~ variation in CO_2 ~~Emissions~~emissions

The CO_2 emissions from different vegetation cover types showed significant seasonal fluctuations, with certain months showing higher emissions than others (Fig.3a). Wildfires had lower CO_2 emissions in July and August, which may correspond to the respective wet seasons (Fig. 3a). ~~Wet conditions usually reduce the occurrence rate of fires (Fig. 4).~~ Forest, shrub, and

grassland fire CO_2 emissionss had higher emissions in February, March, and April, possibly related to the dry weather and accumulation of combustible materials in spring, increasing the risk of fires (Fig. 3b-d). The extreme fire CO_2 emissions observed in 2003 and 2008 were both associated with prolonged drought conditions during the spring season. Cropland fire sCO_2 emissions showed significant emission peaks in April, May, and June (Fig. 3e). This pattern may be related to specific agricultural activitiesy (such as plowing, sowing, and harvesting) cycles, as cropland fires often occur after harvest when crop residues are burned to prepare for the next planting season. The spatial distribution of forest, shrub, and grassland fire emissions were was relatively similar among the different months (Figs. S1-S3). In contrast, the spatial distribution of CO_2 emissions from cropland fires varied significantly across different months and was likely influenced by policy management (Fig. 54). High emissions in March and April were concentrated in NE region, while emissions in May and June were primarily associated with the NC region. The regional difference in peak emission months can be attributed to distinct cropping systems and climatic conditions. In the NE region (e.g., Heilongjiang and Jilin), cold winters and delayed spring thaw often push straw burning activities into March-April, following the autumn harvest. In contrast, the NC region (e.g., Anhui, Henan, Jiangsu) practices a double-cropping system of winter wheat and summer maize, where wheat is harvested in May-June, and burning of straw residues is typically observed during this transition period. The high emissions of cropland fires in March and April mainly originated from Heilongjiang and Jilin Provinces. The high emissions of cropland fires in May and June mainly came from the Anhui, Henan, and Jiangsu Provinces.

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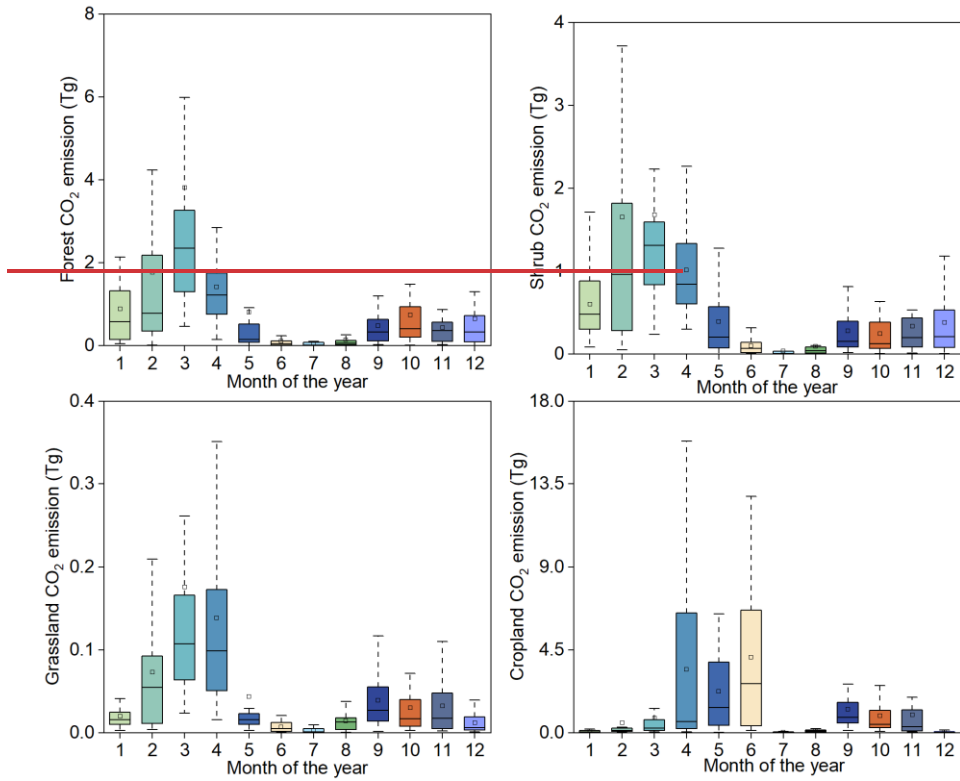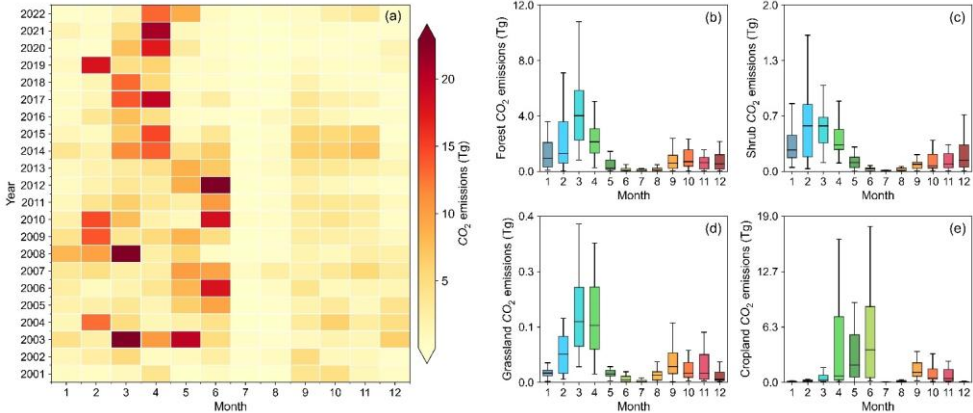
Figure 4: Box plots of CO$_2$ emissions for specific vegetation cover types per month from 2001 to 2022 in China, showing the median (black line), mean (box), and the range within 1.5 times the interquartile range (IQR): (a) Forest, (b) Shrub, (c) Grassland, (d) Cropland.Figure 3: (a)Heatmap of monthly total wildfires CO$_2$ emissions in China from 2001 to 2022; box plots of CO$_2$ emissions for specific vegetation cover types per month from 2001 to 2022 in China, showing the median (black line), mean (box), and the range within 1.5 times the interquartile range (IQR): (b) Forest, (c) Shrub, (d) Grassland, (e) Cropland.

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monthly CO$_2$ emissions(unit:10^6 g)

| | 0-110 | | 110-150 | | 150-180 | | 180-200 | | >200 |
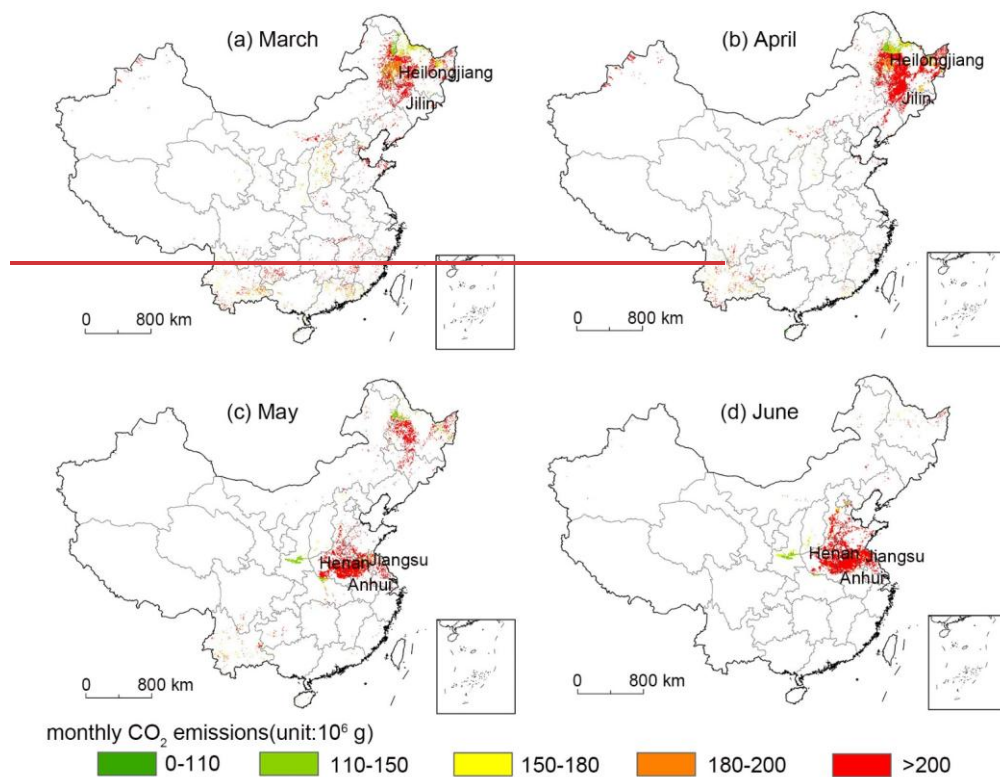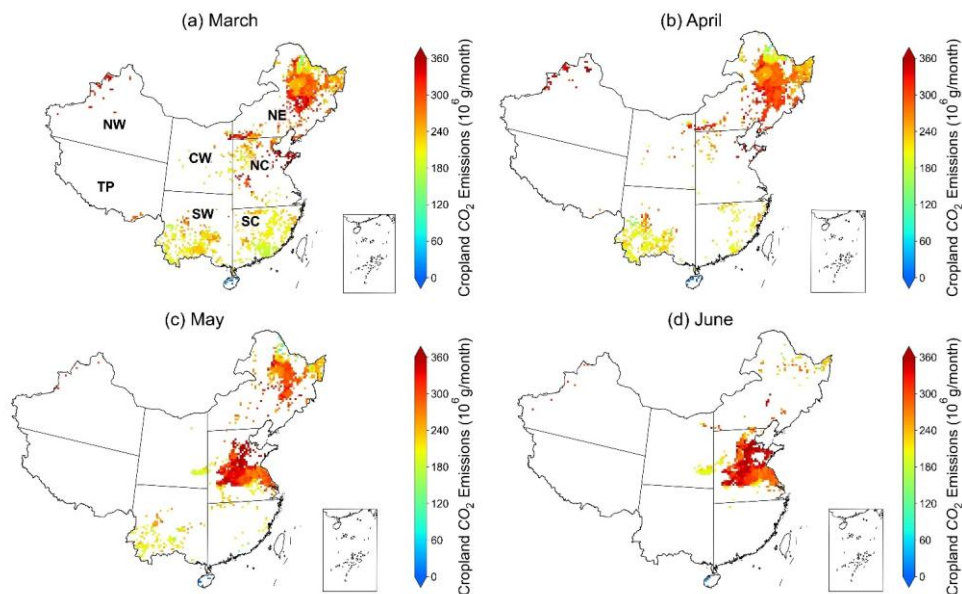
Figure 54: Spatial distribution of monthly CO₂ emissions within cropland fires from 2001 to 2022 in China: (a) March, (b) April, (c) May, and (d) June. The original emission data at 500 m resolution were resampled to 0.25° grid to enhance visual clarity.

3.3 Spatiotemporal ~~Variations~~ variations in CO₂ ~~Emissions~~emissions

Due to differences in geographical location, climate conditions, and population density, the spatiotemporal distribution of CO₂ emissions in each region exhibits heterogeneity (Fig. 56). emissions in NW, CW, and TP regions were relatively low, accounting for only 3% of China's annual average emissions from 2001 to 2022. In contrast, regions with high emissions were mainly concentrated in NE, NC, SC, and SW regions (Fig. 5a).

To assess whether wildfire CO₂ emissions exhibit statistically significant spatial clustering patterns at the national scale, we first applied Moran's I. This step was crucial because it determined the necessity of subsequent local cluster analyses (such as hotspot analysis).~~Overall, the emissions in the northwestern region of China were relatively low. The significant areas with higher emissions were mainly concentrated in China's eastern and central regions (Fig. 6a). The areas with high CO₂ emissions from forest fires were mainly in the northeast and southwest regions (Fig. 6b). The distribution of high CO₂ emissions from shrub fires was relatively scattered. However, there were some concentrated high-emission areas in the western and northeastern regions (Fig. 6c). The emissions from grassland fires were generally low and were mainly concentrated in~~

Northeastern China (Fig. 6d). The high-value areas of CO$_2$ emissions from cropland fires were mainly concentrated in eastern China (Fig. 6e).

The results (Table 1) showed significantly positive Moran's I values for fire emissions across all vegetation types ($I > 0$, $p < 0.01$; $Z > 2.58$), indicating non-random spatial distributions and strong global spatial autocorrelation. These findings supported the use of the Getis-Ord Gi* statistic to identify statistically significant hotspots and coldspots of wildfire emissions. Additionally, the presence of spatial autocorrelation implies the need for spatially explicit regression models (e.g., Geographically and Temporally Weighted Regression), as global models such as Ordinary Least Squares (OLS) may not adequately capture the spatial heterogeneity in emission-driver relationships. The results of the global spatial autocorrelation analysis of CO$_2$ emissions from wildfires are shown in Table 1. Under different wildfires, the p values were all less than 0.01, with a confidence level of 99%; the Moran's I values were all positive, with a Z score greater than 2.58, indicating a significant positive spatial autocorrelation of CO$_2$ emissions from wildfires, exhibiting an aggregation pattern in spatial distribution.

Table 1. Global spatial autocorrelation statistics of CO$_2$ emissions

Vegetation cover type	Moran's I	Z	p	Clustering pattern
Forest	0.680.052	64.905.072	0.000	Cluster
Shrub	0.990.118	91.508.961	0.000	Cluster
Grassland	0.600.064	58.956.632	0.000	Cluster
Cropland	0.890.281	106.5020.414	0.000	Cluster
All	0.600.110	83.158.894	0.000	Cluster
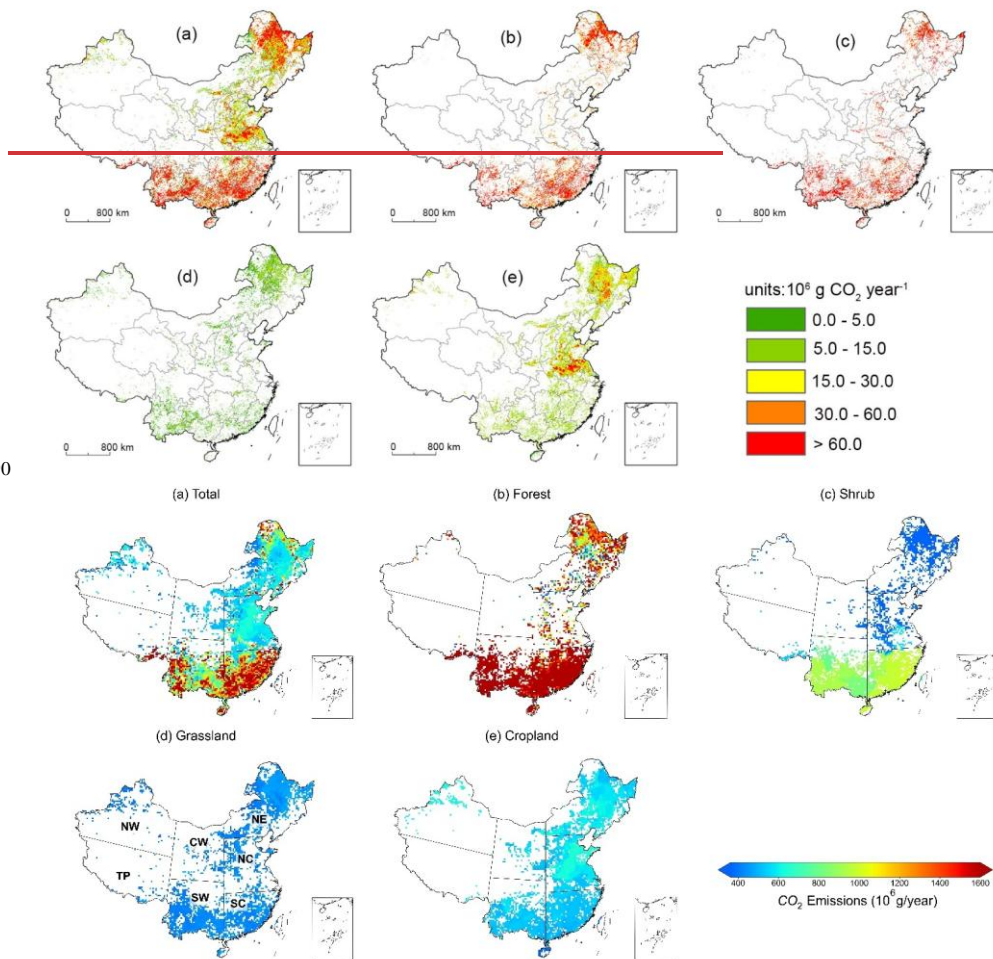
Figure 56: Average annual spatial distribution of CO$_2$ emissions in China from 2001 to 2022: (a) all fire types, (b) Forest, (c) Shrub, (d) Grassland, and (e) Cropland. The original emission data at 500 m resolution were resampled to 0.25° grid to enhance visual clarity.

Based on the Getis-Ord Gi* analysis (Fig. 6), we identified clear spatial clusters of persistent high (hotspots) and low (coldspots) wildfire CO$_2$ emissions (Fig. 6). Among different vegetation types, CO$_2$ emissions from forest fires are mainly

distributed in NE, SW, and SC regions, with the NE region accounting for 56% of China's annual average emissions from 2001 to 2022 (Fig. 5b). The NE region (e.g., the Greater and Lesser Khingan Mountains) is a typical coniferous forest belt with abundant fuel accumulation, dry and windy spring conditions, and makes it highly prone to intense but infrequent wildfires (Lian et al., 2024a). However, despite the high forest fire emissions in NE, no significant hotspots were detected by the Getis-Ord Gi* analysis (Fig. 6b), indicating that its high emissions mainly stem from sporadic extreme events rather than persistent clustering (Fig. 7a). For example, in 2003 and 2008, extreme wildfires in NE China contributed 73% and 56% of the national forest fire CO_2 emissions in 2003 and 2008, respectively (Fig. 7a). In contrast to NE, SW and SC exhibited significant spatial clustering in forest fire CO_2 emissions. Forest fires in these regions are prone to occurring in late winter and early spring each year, with relatively small fire scales but high frequency (Qin et al., 2014; Zhang et al., 2023a). The hotspot analysis of wildfire CO_2 emissions investigated the specific spatial clustering of CO_2 emissions, as shown in Figure 7. In general, the high values of CO_2 emissions were mainly concentrated in the eastern regions of Heilongjiang and Inner Mongolia Provinces in China from 2001 to 2022, with annual emissions accounting for 44% of the total annual emissions (Fig. 7a). There was only one high-value aggregation area for forest fires and grassland fires, which is similar to the spatial distribution of total emissions (Fig. 7b and Fig. 7d). The average annual emissions of high-value aggregation areas accounted for 53% and 64% of the total annual emissions, respectively. There were two high-value clusters of shrub fires, one in the eastern regions of Heilongjiang and Inner Mongolia Provinces and the other in the southwestern forest areas, with annual emissions accounting for 25.82% and 40% of the total emissions, respectively (Fig. 7c). There were also two high-risk areas for cropland fires, one in the eastern regions of Heilongjiang and Inner Mongolia Provinces and the other in the eastern and central regions of China, mainly including Shandong, Henan, Anhui, and Jiangsu (Fig. 7e). The average annual emissions accounted for 43% and 48% of the total emissions, respectively. It is worth noting that northeastern China is marked as a high-confidence hotspot area among all fire types, which may indicate the long-term existence of high CO_2 emissions in the region.

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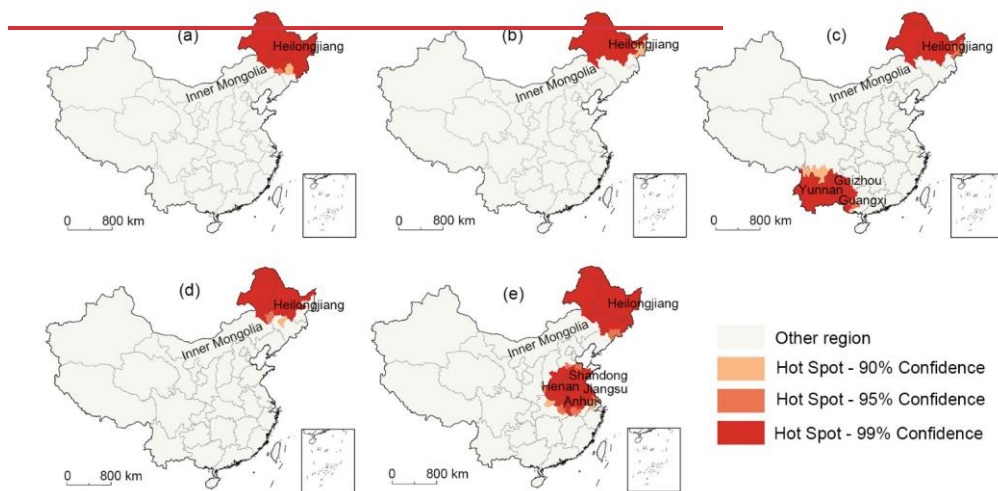
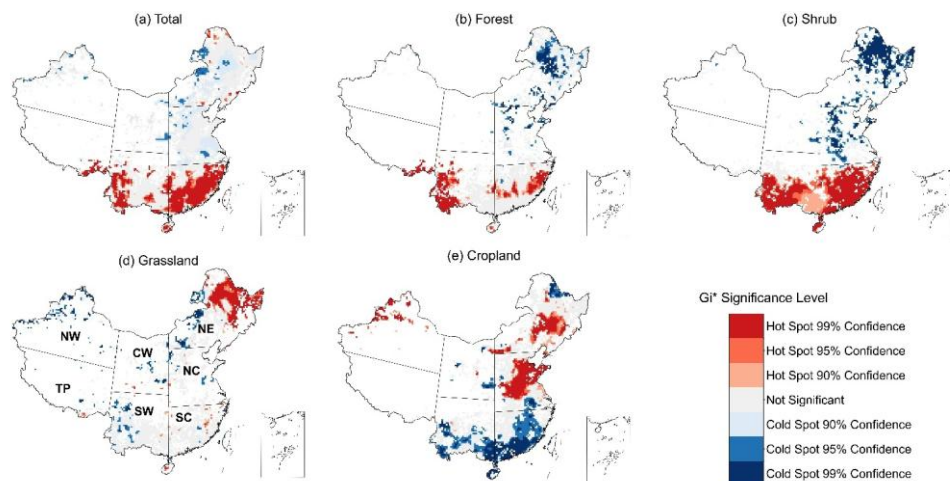

420 **Figure 7̶6̶: Spatial Clustering of CO$_2$ emissions at 0.25° resolution in China (Gi* Hot Spot Analysis)**~~Spatial distribution of CO$_2$ emission hotspots from 2001 to 2022 in China~~: **(a) all fire types, (b) Forest, (c) Shrub, (d) Grassland, and (e) Cropland. Red areas represent statistically significant clusters of high emission values (hot spots), while blue areas indicate significant low-value clusters (cold spots), with confidence levels of 90%, 95%, and 99%.**

Shrub fire CO_2 emissions were concentrated in the SW and SC regions, accounting for 47% and 27% of China's annual average emissions from 2001 to 2022, respectively (Fig. 5c). Secondary vegetation such as shrubs and bamboo forests are common in these areas, resulting from land use changes (e.g., farmland abandonment, forest degradation), which facilitates the accumulation of combustibles (Han et al., 2018). Meanwhile, complex terrain and high biomass also amplify the risk of fire spread (He et al., 2024). Additionally, seasonal drought (low humidity) combined with human activities such as fuelwood collection and traditional burning practices (Ying et al., 2021) exacerbate fire occurrences, forming persistent spatial clustering that has been clearly identified as hotspot areas (Fig. 6c).

Grassland fire emissions were mainly concentrated in the NE region, accounting for 70% of the China's annual mean during 2001- 2022 (Fig. 5d), with hotspot areas focusing on the grasslands of Inner Mongolia (e.g., Hulunbuir, Xilingol) (Fig. 6d). In this region, dry herbaceous vegetation, strong winds, and low humidity in spring make grassland fires extremely prone to ignition (Chang et al., 2023). Additionally, there is a close relationship between land use and grassland fire occurrence (Li et al., 2017). Li et al. (2017) explored the relationship between land use and the spatial distribution of grassland fires, and the results showed that land use has a significant impact on grassland fires.

High CO_2 emissions from cropland fires were concentrated in NC and NE regions, accounting for 51% and 42% of the China's annual mean emissions, respectively, during 2001-2022 (Fig. 5e). Spatiotemporally, from 2003 to 2012, the main emission sources were agricultural provinces in NC (e.g., Hebei, Shandong, Henan, Anhui), while after 2012, agricultural regions in NE (e.g., Heilongjiang, Jilin, Liaoning) became the primary sources of emissions (Fig. 6e and Fig. 7d). These areas have high crop straw yields and long-standing traditional burning practices, making them typical hotspots of agricultural fires (Li et al., 2024a; Wu et al., 2018).For emissions from different vegetation cover types, some years and regions exhibit unexpectedly high emissions, potentially caused by special events such as abnormal climate conditions, human activities, and fire management. Figure 8 shows the time series of high-emission regions under the different vegetation cover types from 2001 to 2022. Extreme forest fires occurred in Heilongjiang and Inner Mongolia Provinces in 2003, and the total emissions of these two provinces accounted for 73% of the total emissions in 2003 (Fig. 8a). The high emissions in 2008 were due to forest fires in Inner Mongolia, which accounted for 47% of the total emissions in 2008. Shrub fire emissions peaked in 2003 and 2010 (Fig. 8b). The emissions in 2003 occurred mainly in Yunnan, Inner Mongolia, and Heilongjiang, with the total emissions from these three provinces accounting for 63% of the total emissions. The emissions in 2010 occurred mainly in Yunnan and Guizhou, accounting for 78% of the total emissions in 2010. Grassland fire emissions also peaked in 2003 and 2008, with the 2003 main emission areas being Inner Mongolia and Heilongjiang, accounting for 85% of the total emissions for that year. Inner Mongolia was the central emission region in 2008, accounting for 62% of the total emissions for that year (Fig. 8c). Human activities and fire management may affect cropland fire emissions more significantly, resulting in more significant variability in CO_2 emissions across provinces (Fig. 8d). Heilongjiang Province had relatively low emissions from 2001 to 2013, with emissions increasing and trending upward from 2014, where the annual average emissions from 2014 to 2022 were five times greater than the annual average emissions from 2001 to 2013. The primary emission years for the Anhui and Henan Provinces were between 2006 and 2014, with emissions decreasing after 2015. The emission trend in Jilin Province was similar

to that in Heilongjiang Province, with higher emissions in recent years. In other regions, CO_2 emissions from cropland fires were relatively high before 2012. After the implementation of China's strict ban on open air biomass burning in 2012, emissions decreased, showing an overall downward trend.

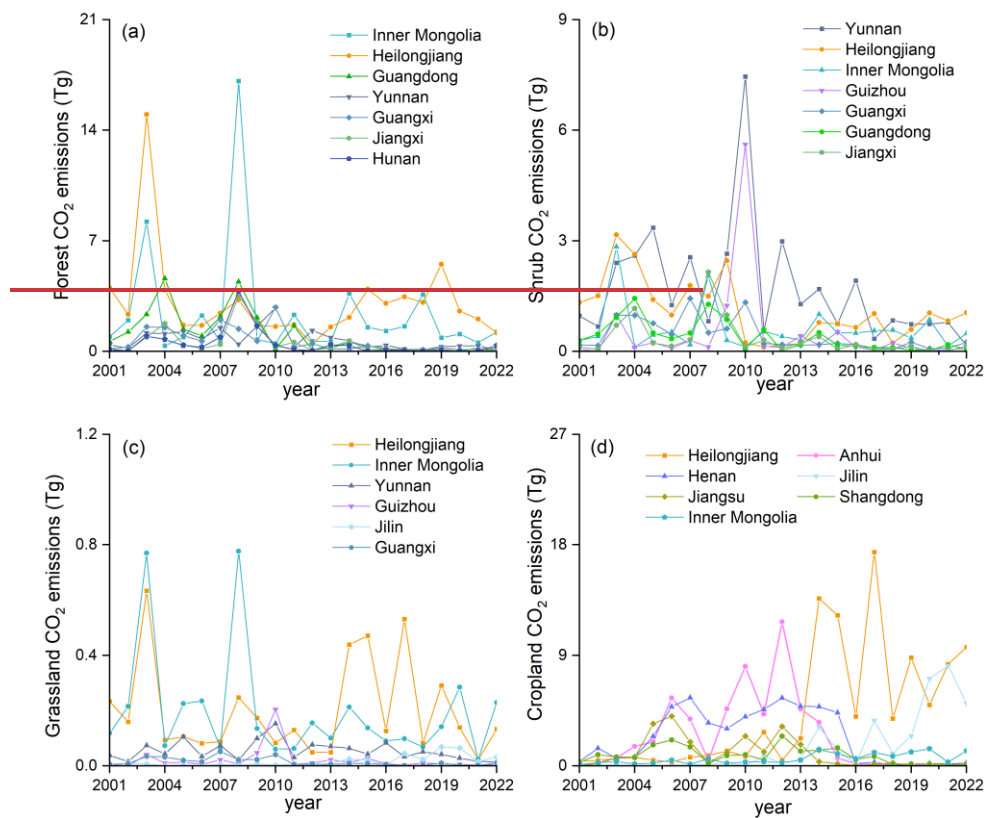
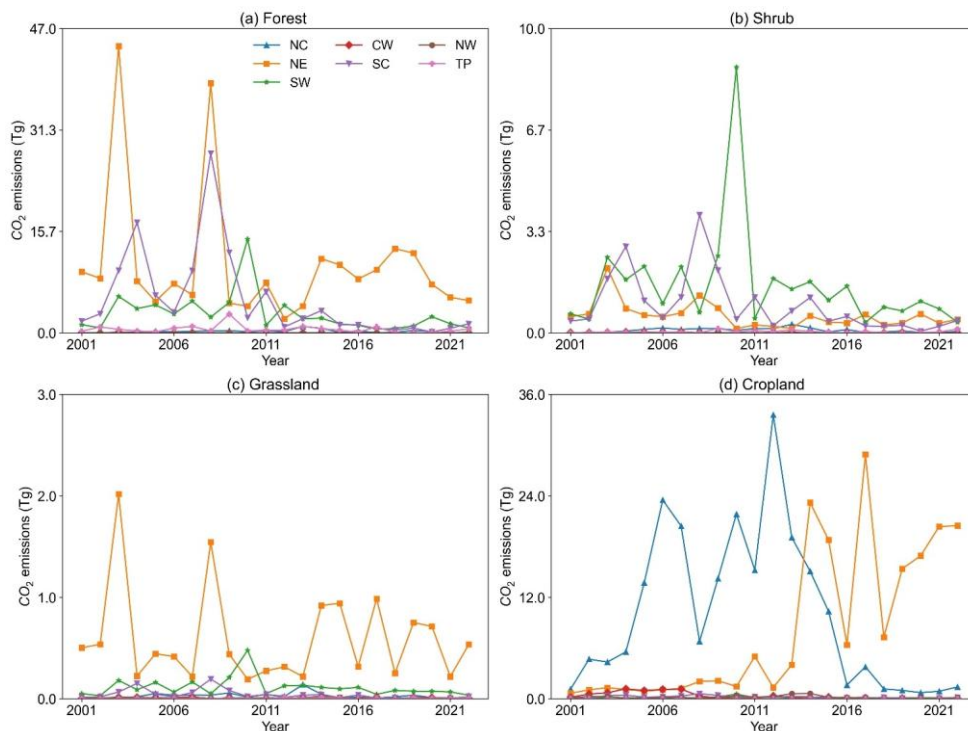
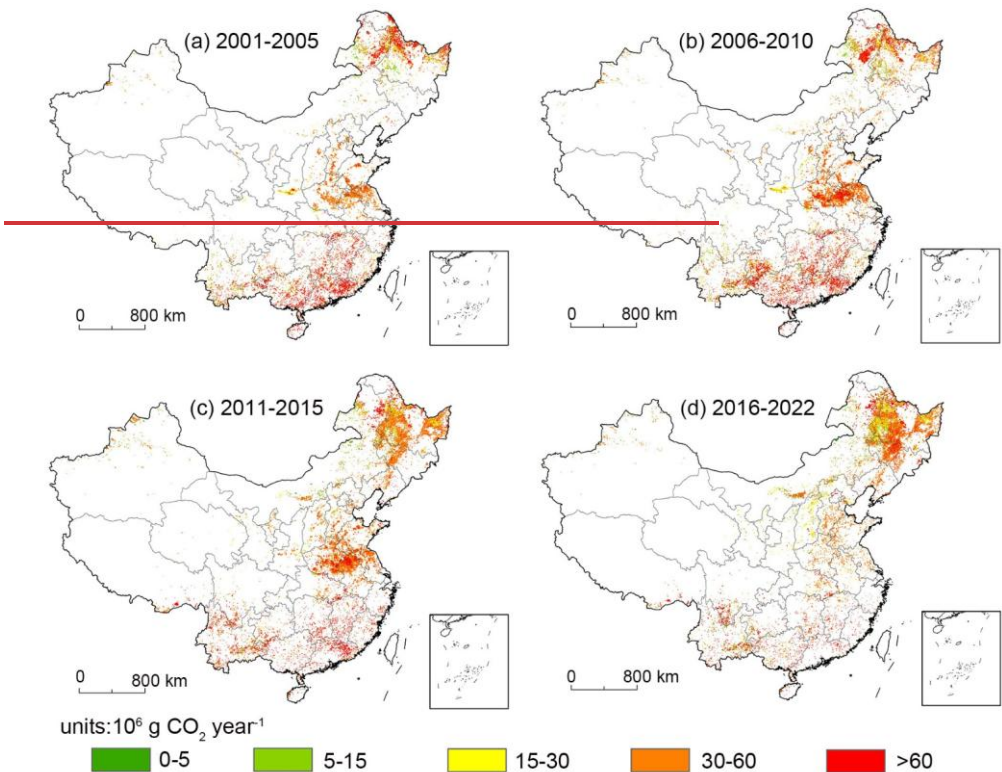



Figure 78: Time series of CO₂ emissions in major regions under different vegetation cover types from 2001 to 2022 in China: (a) Forest, (b) Shrub, (c) Grassland, and (d) Cropland.

465   The spatial distribution of CO₂ emissions changes over different periods from 2001 to 2022 (Fig. 9). The average annual CO₂ emission from 2001 to 2005 was 28.7 Tg, with CO₂ emission mainly concentrated in the eastern region of China (Fig. 9a). The average annual emissions from Heilongjiang and Inner Mongolia accounted for 42% of the total annual emissions. Compared with 2001-2005, the average annual CO₂ emissions increased from 2006 to 2010 (39.8 Tg), and the high-emission areas increased (Fig. 9b). High emissions still existed in Heilongjiang and Inner Mongolia in the east.
470   However, other provinces, such as Anhui and Henan, began to show higher emissions, mainly due to an increase in cropland fires in these provinces (Figs. S4-S7). The average annual CO₂ emissions decreased from 2011 to 2015 (34.9 Tg). Forest fire emissions in Heilongjiang and Inner Mongolia decreased, while cropland fire emissions increased (Figs. S4-S7). High CO₂ emissions from cropland fires still occurred in provinces such as Anhui and Henan (Fig. 9c). The average annual CO₂ emissions from 2016 to 2022 were the lowest of the four time periods (24.4 Tg), with an overall decrease in CO₂ emissions

475 ~~from forest, shrub, and grassland fires (Fig. 9d). CO₂ emissions from cropland fires in various provinces, such as Anhui and Henan, decreased, while high emissions from cropland fires in the eastern regions of Heilongjiang, Inner Mongolia, and Jilin still existed. The average annual emissions from Heilongjiang, Jilin, and Inner Mongolia accounted for 80% of the total annual emissions.~~

units:10^6 g CO_2 year^{-1}

| 0-5 | 5-15 | 15-30 | 30-60 | >60 |

480 ~~**Figure 9: Spatial distribution of annual CO₂ emissions for all types of fires from (a) 2001 to 2005, (b) 2005 to 2010, (c) 2011 to 2015, and (d) 2016 to 2022.**~~

3.4 The impact of factors on wildfires in China

Wildfires in China exhibit distinct spatial clustering patterns. To investigate the climatic and socio-economic drivers of wildfire CO_2 emissions and to characterize their spatiotemporal heterogeneity, we applied three regression models—OLS,

485 Geographically Weighted Regression (GWR), and GTWR—to four types of fires (forest, shrub, grassland, and cropland). We compared model performance using R^2 and the AICc. Explanatory variables were selected based on theoretical relevance and data availability for the period 2001-2019. As shown in Table 2, these variables include five climatic factors—punctual temperature (TMP, °C), accumulated precipitation (PRE, mm), relative humidity (RH, %), wind speed at 2m (WIN, m/s), and daily cumulative sunshine hours (SSD, h)—and two socio-economic indicators: gross domestic product (GDP, millions/km^2)

490 and population density (POP_DEN, people/grid). These factors are widely recognized as influencing wildfire emissions (Lan et al., 2021; Ma et al., 2020; Zeng et al., 2024). TMP and SSD affect fuel flammability and combustion efficiency, PRE and RH regulate fuel moisture, and WIN promotes fire spread. Socio-economic factors reflected anthropogenic influences on fire ignition, suppression, and land-use. To ensure model parsimony and statistical robustness, variables that were not statistically significant ($p > 0.05$) in the global OLS model were excluded from subsequent GWR and GTWR analyses. All retained

495 variables were normalized or Box-Cox transformed prior to modeling to ensure comparability.

Table 2 Driving factors and sources

Driving factors	Abbreviation	Source
Punctual temperature	TMP	
Relative humidity	RH	Daily meteorological dataset of essential
Accumulated precipitation	PRE	meteorological elements of China National
Wind speed (2 m)	WIN	Surface Weather Station (V3.0)
Daily cumulative sunshine hours	SSD	
Gross domestic product	GDP	Chen et al. (2022)
Population density	POP_DEN	LandScan Global (Bright et al., 2001-2022)

Across all fire types, both GWR and GTWR models outperformed the global OLS model. For forest fires, GTWR achieved the best performance ($R^2 = 0.58$; AICc = 128,909), while OLS explained only 6% of the variance, indicating strong

500 spatiotemporal heterogeneity. For cropland fires, GTWR also performed well ($R^2 = 0.52$; AICc = 141,335), highlighting the influence of cropping cycles and regional factors. In shrub fires, the performance of GWR and GTWR models was nearly identical (both with $R^2 = 0.87$), and GTWR showed a slightly higher AICc (worse model fit), indicating that incorporating temporal weights did not lead to a substantial improvement. This suggests that shrub fire emissions are primarily driven by spatial heterogeneity, with limited temporal variability. For grassland fires, GTWR improved R^2 from 0.27 to 0.31 compared

505 to GWR, but overall model fit remained low, indicating that other drivers—such as land use change, grazing, or local policies— play a critical role in grassland ecosystems.

Table 3. Comparison of regression results for different fire types using OLS, GWR, and GTWR models.

Fire type	Model	Intercept	PRE	TEP	RH	WIN	SSD	GDP	POP_DEN	R^2	AICc
	OLS	2698	49	727*	-259*	-864*	-100*	-2321*	-110*	0.06	135428

Forest	GWR	3260	-	-436	-145	-200	91	-1983	-186	0.49	130508
	GTWR	3204		-524	-205	-161	126	-469	-888	0.58	128909
Shrub	OLS	385	-303*	583*	246*	-162*	-384*	11*	20*	0.27	104143
	GWR	733	-31	111	100	5	-61	-10	-1	0.87	90837
	GTWR	733	-31	110	101	3	-57	-11	0	0.87	91034
Grassland	OLS	144	10	-69*	23*	-3*	-20*	-4*	1*	0.10	81654
	GWR	130	-	-40	18	-6	-5	-6	-4	0.27	79908
	GTWR	131	-	-40	19	-5	-4	-20	-4	0.31	79702
Cropland	OLS	239	25	-12*	-44*	14*	80*	2*	0*	0.10	149703
	GWR	230	-	11	-31	16	2	50	3	0.42	143770
	GTWR	228	-	16	-29	16	2	36	4	0.52	141335

Note: * An asterisk next to a number indicates a statistically significant p-value ($p < 0.01$).

To explore the temporal dynamics of individual variables, Figure 8 presented annual average GTWR regression coefficients for 2001-2019, revealing significant differences in how climatic and socioeconomic drivers influenced wildfire CO_2 emissions across vegetation cover types. Except for SSD, all other factors exhibited negative effects on forest fire CO_2 emissions (Fig. 8a). Temporally, regression coefficients for key variables such as POP_DEN, TMP, and GDP showed weakened negative effects after 2012, suggesting reduced sensitivity of forest fire emissions to these drivers in recent years. This change likely reflects strengthened forest fire prevention policies and management measures implemented in China after 2012 (Fig. 12), which significantly reduced fire occurrences. Spatially, regression coefficients showed significant north-south disparities (Fig. 9). TMP and RH had a dual effect on forest fire emissions. In NE and NC regions, TMP, and RH positively correlated with forest fire emissions, indicating that warming and drying conditions may promote fire activity in temperate forests (Fang et al., 2021; Lian et al., 2024b) (Fig. 9a and 9b). In contrast, in SW and SC regions, TMP and RH exhibited negative coefficients (Fig. 9a and 9b). This may occur because, while high temperatures can increase plant evapotranspiration and reduce fuel moisture content (Chuvieco et al., 2004), China's monsoon climate typically links high temperatures with high relative humidity, creating a threshold effect on forest fires (Ma et al., 2020). Additionally, during high-temperature periods, forest fire prevention authorities implement strict fire control measures, limiting fire occurrences (Abatzoglou et al., 2018; Hu and Zhou, 2014). GDP (Fig. 9e) showed positive effects in the NE region, but negative effects in SC and SW regions. Similarly, POP_DEN (Fig. 9f) generally displayed negative effects, especially in SW and SC regions, highlighting the role of human presence in fire suppression.

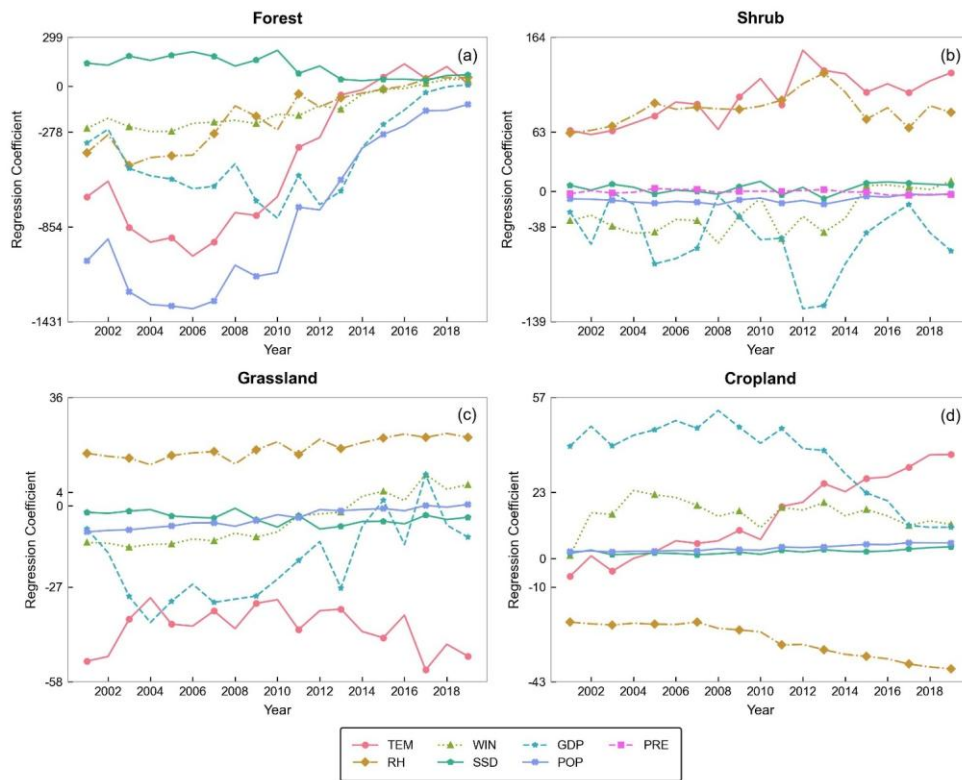
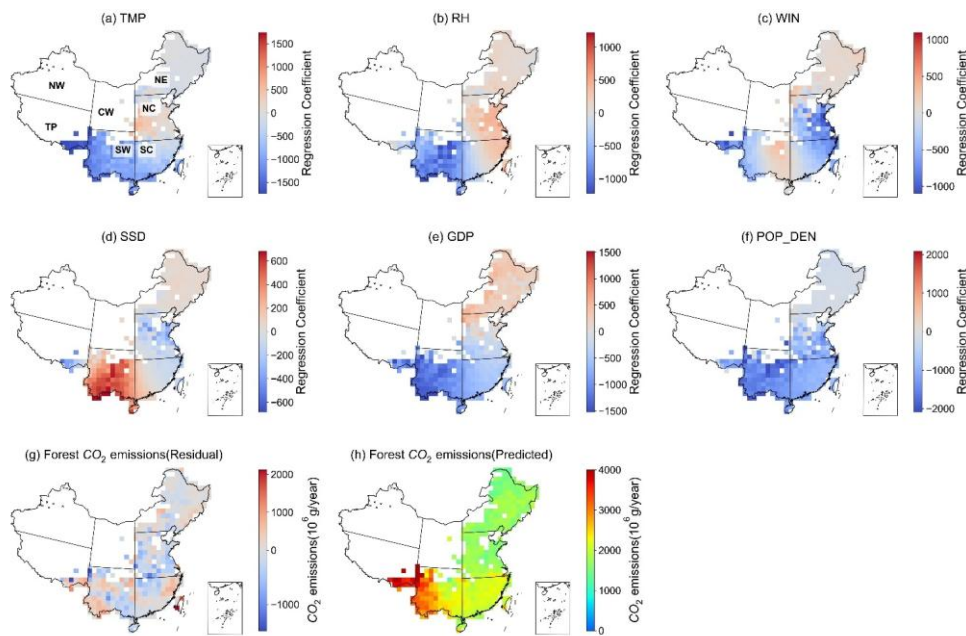



Figure 8: Temporal evolution of GTWR regression coefficients for wildfires CO$_2$ emissions across four vegetation cover types in China (2001–2019). Positive and negative values indicate the direction and magnitude of each variable's influence on CO$_2$ emissions.

530 **Figure 9: Spatial distribution of GTWR regression coefficients for forest fire CO₂ emissions and their driving factors across China. The maps illustrate GTWR coefficients of six environmental and socioeconomic variables: (a) temperature, (b) relative humidity, (c) wind speed, (d) daily cumulative sunshine hours, (e) gross domestic product (GDP), and (f) population density. Grey regions represent areas where the intercept was zero (i.e., no valid model fit), and black × symbols mark locations where the regression coefficients did not pass the significance test ($p \geq 0.05$). Figure (g) and (h) show the model residuals and predicted shrubland CO₂**
535 **emissions.**

Shrub fires CO₂ emissions were well-captured by GWR and GTWR, dominated by spatial heterogeneity with minimal temporal variation (Table 3). GTWR showed that TMP and RH were consistent positive drivers throughout the study period, while GDP and WIN had negative effects, with other variables exerting minor influences (Fig. 8b). Spatially, TMP showed a positive effect across most regions (Fig. 10a). RH showed significant positive local effects in NC region, reflecting that humid

540 climates promoted shrub growth and fuel accumulation (Fig. 10c) (Lian et al., 2024b; Liu et al., 2024). Once ignited by human activity or spring droughts, abundant fuel intensified fire severity and CO₂ emissions. In contrast, WIN and GDP exerted strong negative effects in parts of NC, likely due to effective fire control practices (Fig. 10d and 10f). Notably, a considerable number of grid cells along the northeastern border failed significance tests for at least one explanatory variable (marked as black dots in Fig. 10a-g). This may be due to limited shrub coverage or mixed land types, leading to low fire frequency and weak emission

545 signals (Lin et al., 2024; Yang and Jiang, 2022). Additionally, many of these non-significant grids are located near international

borders, particularly adjacent to Russia. Since the GTWR model is limited to Chinese territory, therefore, it lacks information on cross-border fire activity, land use, and policy context (Li et al., 2024b; Lin et al., 2024; Quan et al., 2022). In northeastern China, transboundary fire spread is a known ignition source and may contribute to CO_2 emissions that are not well explained within national data coverage.

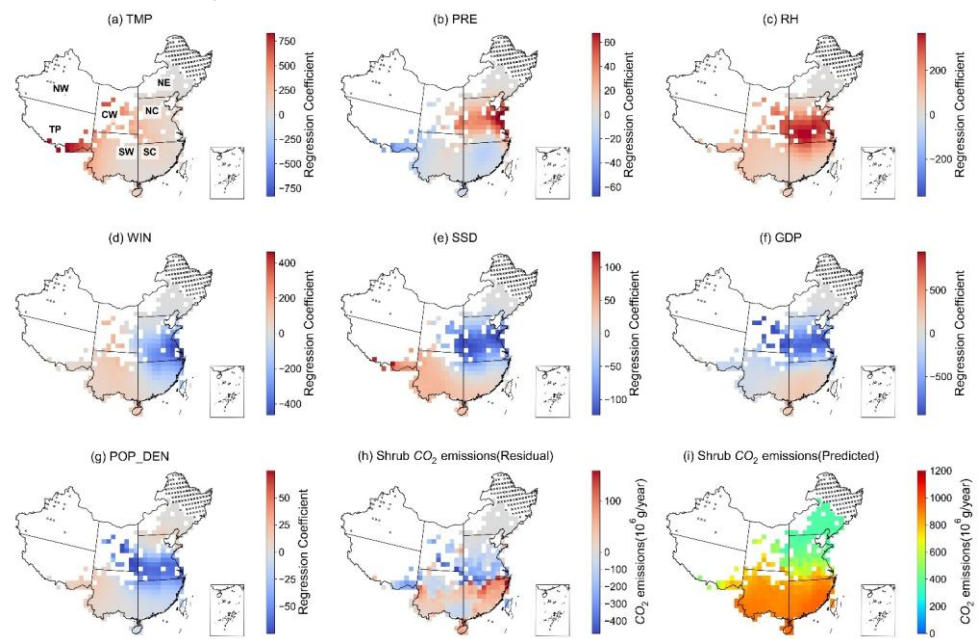



Figure 10: Spatial distribution of GTWR regression coefficients for shrub fire CO_2 emissions and their driving factors across China. The maps illustrate GTWR coefficients of seven environmental and socioeconomic variables: (a) temperature, (b) precipitation, (c) relative humidity, (d) wind speed, (e) daily cumulative sunshine hours, (f) gross domestic product (GDP), and (g) population density. Grey regions represent areas where the intercept was zero (i.e., no valid model fit), and black × symbols mark locations where the regression coefficients did not pass the significance test ($p \geqslant 0.05$). Figure (h) and (i) show the model residuals and predicted shrubland CO_2 emissions.

From a temporal perspective, the GTWR results for cropland fires CO_2 emissions showed that RH had a negative effect, and this negative influence gradually strengthened (Fig. 8d). GDP primarily exhibited a positive effect, but its positive influence gradually weakened. The impact of TMP shifted from negative to positive, with its effect gradually increasing. WIN mainly exerted a positive effect, while other factors had weak influences. Spatially, TMP showed strong positive coefficients in eastern and central China (Fig. 11a). Straw burning activities in these regions peaked in spring and autumn, a pattern closely linked to rising temperatures. In contrast, negative temperature coefficients in southern and southwestern China suggest that

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higher temperatures in these regions, often accompanied by high humidity or stricter fire regulations, may suppress fire activity. RH exhibited a significant negative effect across most parts of China, likely due to increased moisture content in agricultural residues, which hinders ignition and combustion (Fig. 11b). WIN showed a positive influence in CW, NC and SC regions, where expansive cropland areas may enable wind to accelerate fire spread during burning events (Fig. 11c). GDP mainly showed positive effects, but after 2010, this gradually weakened (Fig. 11e and Fig. 8d). This trend may be attributed to increased straw production driven by agricultural expansion in economically developed regions, where straw utilization infrastructure had not yet caught up, resulting in elevated emissions. Early GDP growth likely brought more crop yields and straw generation, thereby enhancing CO_2 emissions(Ren et al., 2019). However, after 2012, this trend reversed as nationwide straw burning bans were introduced. Regions with higher economic development began to demonstrate stronger emission control capacity, leading to a gradual weakening of GDP's positive effect on emissions (Zeng et al., 2024).
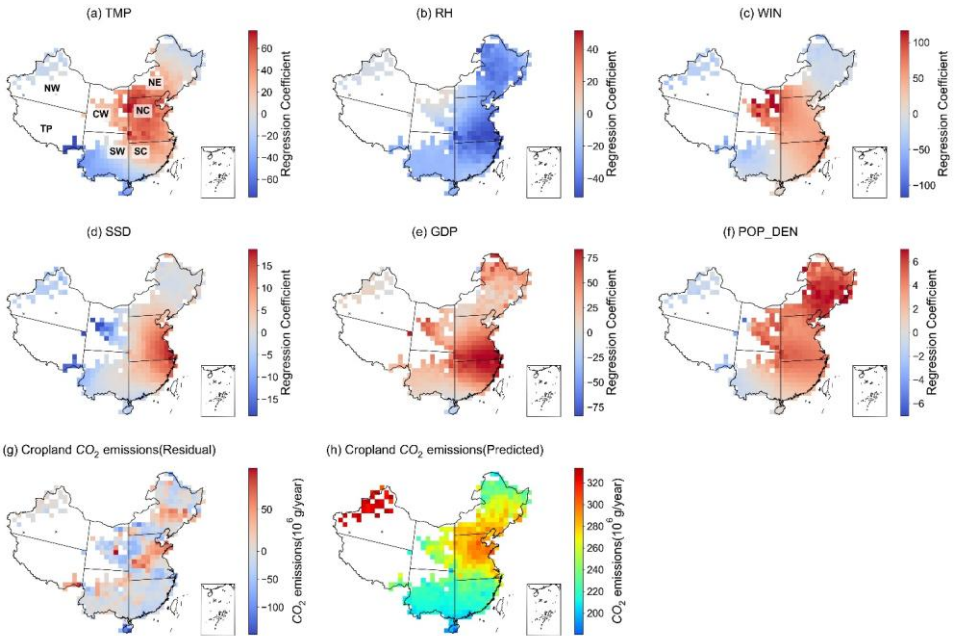
Figure 11: Spatial distribution of GTWR regression coefficients for cropland fire CO_2 emissions and their driving factors across China. The maps illustrate GTWR coefficients of six environmental and socioeconomic variables: (a) temperature, (b) relative humidity, (c) wind speed, (d) daily cumulative sunshine hours, (e) gross domestic product (GDP), and (f) population density. Grey regions represent areas where the intercept was zero (i.e., no valid model fit), and black × symbols mark locations where the regression coefficients did not pass the significance test ($p \geq 0.05$). Figure (g) and (h) show the model residuals and predicted shrubland CO_2 emissions.

580   Although the GTWR model indicated that climatic and socioeconomic variables such as TMP, RH, and GDP explained the spatial variation in wildfire CO_2 emissions, the overall model performance remains moderate for forest and shrub fires, with particularly low explanatory ability for grassland fires (R_2^2 = 0.31). This gap suggests that, beyond natural and socioeconomic factors, other key drivers may have been omitted. Multiple studies (Gao et al., 2023; Kelly et al., 2013; Phillips et al., 2022; Xie et al., 2020) highlight the substantial impact of fire management policies on CO_2 emissions. For instance,

585 Phillips et al. (2022) showed that the marginal abatement cost of avoiding fire-related CO_2 emissions through fire management is comparable to or even lower than that of many other climate mitigation strategies.

   In China, the role of policy is particularly significant. Wu et al. (2018) reviewed 51 crop straw management regulations issued between 1965 and 2015, with 34 implemented after 2008. The timing of these intensive regulatory efforts closely aligns with key turning points in emission trends (Fig. 12). For cropland fires, annual CO_2 emissions increased from 8.2 Tg/year

590 during 2001-2005 to 26.2 Tg/year during 2010-2016, but began to decline following the revision of the Air Pollution Prevention and Control Law in 2015 and the launch of the Air Pollution Action Plan in 2013. Similarly, after the implementation of the National Forest Fire Prevention Plans in 2009 and 2016, CO_2 emissions from forest, shrub and grassland fires dropped from 38.1 Tg/year (2006–2009) to 13.3 Tg/year (2017–2022). Jin et al. (2022) further estimated that over 80% of wildfire-related CO_2 emissions could be avoided under effective fire management. These findings strongly indicate that

595 policy management plays a critical role in wildfire CO_2 emissions.

   Notably, northeastern China is the only region where cropland burning has increased in recent years, highlighting the need for adaptive rather than restrictive policies. As one of China's major grain-producing regions, Northeast China generates large volumes of straw. Harsh winters and short windows for straw return or removal, combined with long-established farming practices, have made complete bans on straw burning particularly challenging. Prior to strict open-burning prohibitions,

600 farmers often burned straw in a dispersed, low-intensity manner, making detection by satellite-based fire products difficult, potentially resulting in systematic underestimation of early emissions. After the implementation of strict bans, facing growing pressure from unprocessed straw accumulation, therefore, some local governments adopted more adaptive fire management policies, such as designating burning windows under favorable meteorological conditions. These "limited and concentrated burning periods" led to spatiotemporally clustered fire events that were more easily captured by remote sensing. In recent

605 years, the Chinese government has also promoted the scientific incorporation of straw into soils, off-field collection, and the industrial utilization of crop residues in Northeast China. These efforts highlight the significant role of policy in shaping emission trends from agricultural burning, particularly in regions where environmental constraints and traditional farming practices pose unique challenges.

~~The factors influencing CO_2 emissions from wildfires are numerous and complex. The Spearman correlation coefficient~~
610 ~~method was utilized to analyze the connection between CO_2 emissions from wildfires in China and various climate factors,~~ ~~such as temperature, precipitation, relative humidity, wind speed, sunshine, and vegetation factors, including vegetation~~ ~~primary productivity and the NDVI. Additionally, the gross domestic product (GDP) and population density were taken into~~ ~~account (Fig. 10). The main factors influencing CO_2 emissions from forest and shrub fires were daily cumulative sunshine~~

hours (forest: 0.41, shrub:0.25; p < 0.001) and NDVI (forest: 0.35, shrub:0.37; p < 0.001), while the main factor affecting
CO_2 emissions from grassland fires was temperature (-0.45, p < 0.001) (Fig. 10a-c). Cropland fires, influenced by human
activities, showed a specific negative correlation with GDP (-0.52, p < 0.001) and population density (-0.51, p < 0.001). At
the same time, other factors had relatively small impacts (Fig. 10d). An increase in GDP and population density was often
accompanied by better agricultural technology and management practices, including more effective management alternatives
to straw burning. Furthermore, changes in fire management may impact CO_2 emissions from wildfires (Gao et al., 2023; Jin
et al., 2022; Kelly et al., 2013; Phillips et al., 2022; Van Wees et al., 2021; Xie et al., 2024). Phillips et al. (2022) found that
the cost of avoiding CO_2 emissions by increasing investment in fire management is comparable to or lower than that of other
mitigation strategies. China's policies have also significantly reduced CO_2 emissions from opening biomass burning fires.
Since the forest fire broke out in the Greater Khingan Mountains region of China on May 6, 1987, China has implemented a
forest fire prevention and control policy of "prevention first, active elimination." Subsequently, local governments have
introduced specific policies on forest, shrub, and grassland fire prevention, successfully reducing the occurrence of forest
and shrub fires in China. The research in this paper also showed that the trend in CO_2 emissions from forest and shrub fires
had decreased significantly since 2001 (Fig. 3a and 3b). Moreover, Jin et al. (2022) reported that from 2001 to 2019,
compared with those of natural wildfires (without strict wildfire management), the average CO_2 emissions generated by
wildfires (forest, shrub, and grassland fires) under management policies decreased by more than 80%.

Table 2 Driving factors and sources

Driving factors	Abbreviation	Source
Punctual temperature	tmp	
Relative humidity	rh	Daily meteorological dataset of essential
Accumulated precipitation	pre	meteorological elements of China National
Wind speed (2 m)	win	Surface Weather Station (V3.0)
Daily cumulative sunshine hours	ssd	
Vegetation primary productivity	NPP	MODIS MOD17A3
Normalized Difference Vegetation Index	NDVI	National Qinghai Tibet Plateau Science Data Center
Gross domestic product	GDP	Chen et al. (2022)
Population density	Pop_den	LandScan Global(https://landscan.ornl.gov/)

* p<=0.05 ** p<=0.01 *** p<=0.001
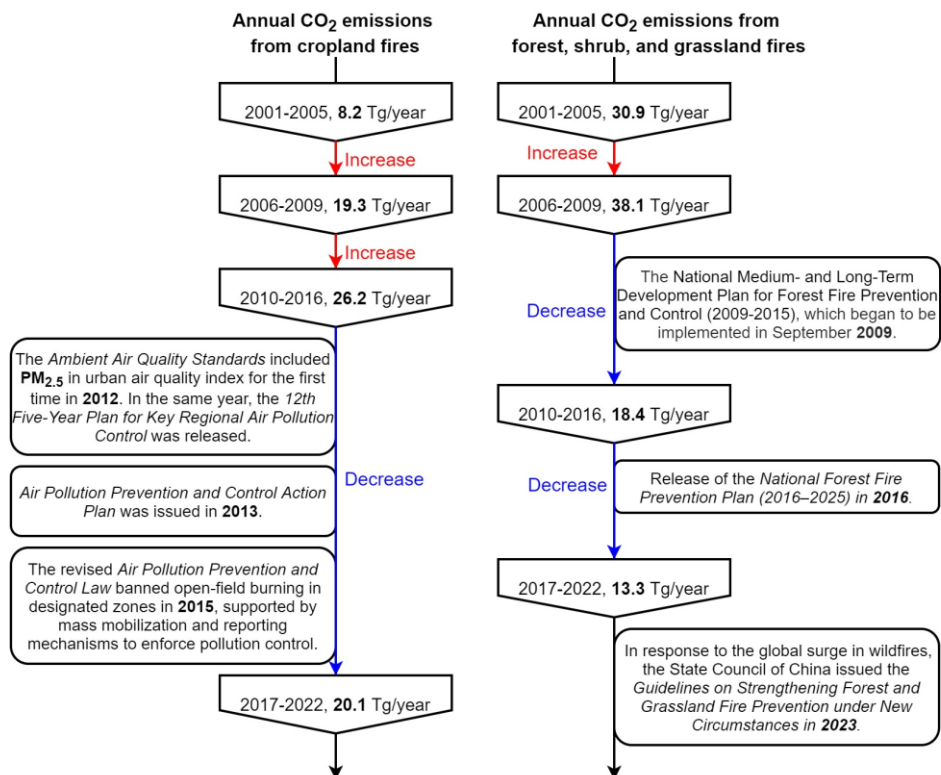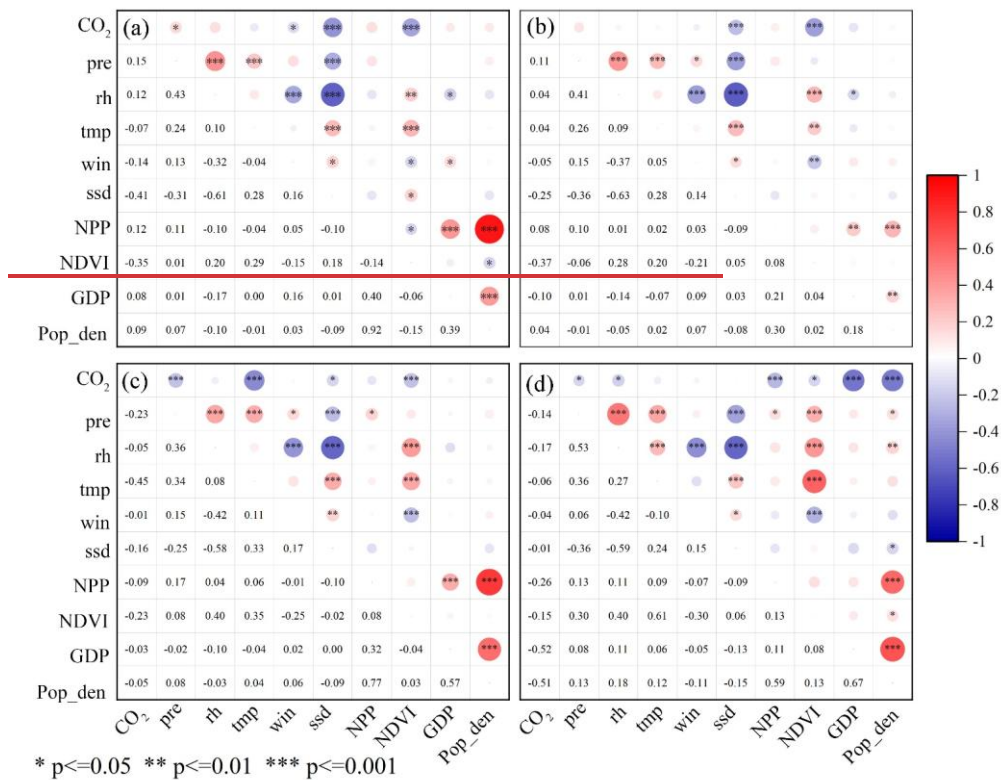
Figure 12. Temporal trends in annual CO_2 emissions from cropland burning and forest, shrub, and grassland fires in China (2001–2022), and key national policy milestones related to fire and air pollution control. ~~Figure 10: Heatmap of Spearman's correlation coefficients between pairs of variables: (a)forest; (b) shrub; (c) grassland; (d) cropland) See Table 2 for variable descriptions.~~

3.5 ~~Implications~~Uncertainty analysis

A Monte Carlo simulation (100,000 iterations) was conducted to assess the uncertainty in the estimated wildfire CO_2 emissions. Monte Carlo simulation is a probabilistic method that generates a large number of possible outcomes based on random sampling from the input parameter distributions, thereby providing a comprehensive assessment of model uncertainty. The uncertainties in emission estimates in this study mainly originated from satellite-derived BA products, AGB, CE, and EF. All parameters, except CE, were assumed to follow normal distributions, as suggested by Zhao et al. (2011). CE values were

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assigned triangular distributions based on vegetation types, with parameter ranges derived from empirical data and literature sources (Junpen et al., 2020; Mieville et al., 2010; Ping et al., 2021; Van Leeuwen et al., 2014; Zhou et al., 2017). For forest and grassland fires, CE was parameterized the FVC-based empirical relationship proposed by Hély et al. (2003), while fixed CE values were applied to shrub and cropland fires. The coefficients of variation (CV) of EF were estimated based on the mean and variability summarized from multiple published sources. Monte Carlo simulations showed that CE and EF contributed less to total emission variability compared to BA and AGB.

Among all parameters, BA emerged as the dominant source of uncertainty. However ,the uncertainty in retrieved from satellite products is difficult to quantify (Hoelzemann et al., 2004; Wu et al., 2018). The MCD64A1 product performs reliably in detecting large fires (Giglio et al., 2018), and its CV was adopted from Giglio et al. (2010). While we also recognize that the MODIS MCD64A1 product tends to underestimate small, fragmented, or low-intensity fires. To evaluate and adjust for this underestimation, we conducted a comprehensive comparison using FireCCI51 (250 m resolution), GFED (500 m resolution), the novel 30-m resolution Global annual Burned Area Map (GABAM, 30 m resolution) (Long et al., 2019), and FINN datasets for the year 2015 (Table S5). The comparison showed that MODIS systematically underestimated burned areas. Despite its higher spatial resolution, GABAM reported smaller cropland fire areas, likely due to its limited temporal resolution. The FINN dataset differed significantly from all other products, with its burned areas generally higher than other data products. Based on these comparisons, we derived a scaling factor (α_i) using the FireCCI51 and GFED datasets and applied them to MODIS burned area estimates. On average, this adjustment increased MODIS-based BA estimates by approximately 1.5 times. To further evaluate the representativeness of our correction method, we compared the standard FINN dataset with a revised version, FINN_VIIR, which incorporates VIIRS active fire detection data (375 m resolution). VIIRS is known to better capture small and short-duration fires often missed by MODIS. Our analysis showed that the burned area in FINN_VIIR was approximately 40% higher than in the standard FINN dataset, which closely aligns with the scaling factor applied in our MODIS-based correction. This consistency provides further support for the effectiveness of our BA adjustment strategy.

AGB is another major contributor to emissions uncertainty. To reflect interannual changes in biomass, we employed the AGB dataset from Su et al. (2016) for the period 2001-2012 and that from Yin et al. (2023) for 2013-2022 for calculating forest fire CO_2 emissions. The mean difference between the two datasets was approximately 7% (100 t/ha vs. 107 t/ha), well within the ±50% uncertainty range reported by Yin et al. (2023), confirming their compatibility for long-term analysis. For shrub fire CO_2 emissions, we employed localized biomass density values from Hu et al. (2006), enhancing the regional representativeness of AGB inputs. For grassland fire CO_2 emissions, we used the index model based on the NDVI developed by Gao et al. (2006). We acknowledge that NDVI-based models may underestimate AGB in dense vegetation due to saturation. To address this, we compared the exponential model by Gao et al. (2012) with the saturation-corrected model by Hu et al. (2024) for alpine meadows in China. The mean AGB estimates were 210 g/m^2 (Gao et al., 2012) and 214 g/m^2 (Hu et al., 2024), with a small difference of 1.9%, well within the reported uncertainty bounds of both models (±62.5 g/m^2 for Gao et al., 2012; ±85 g/m^2 for Hu et al., 2024). Given the broader applicability of Gao's model across diverse grassland types (e.g., arid steppe, wetlands, meadow grasslands), we adopted it for national-scale grassland AGB estimation. For forest, shrub and

grassland fire CO_2 emissions, the uncertainty in AGB was derived from values reported in the literature. For cropland fire CO_2 emissions, AGB was derived from national statistical records, with CV set at 20% (Zhou et al., 2017).

Table 4 presented the total wildfire CO_2 emissions and their associated uncertainty ranges across different vegetation cover types. On average, the estimated uncertainties in CO_2 emissions were (-39%, +76%) for forest fires, (-37%, +20%) for shrub fires, (-26%, +58%) for grassland fires, and (-50%, +51%) for cropland fires. The large uncertainties in forest, shrub, and grassland fire CO_2 emissions were mainly due to uncertainties in AGB and BA estimates. The uncertainty in cropland fire CO_2 emissions uncertainty primarily reflected possible under-detection of BA. Despite these uncertainties, this study incorporated multiple BA datasets, multi-temporal vegetation cover datasets, regionally validated AGB estimates, and a comprehensive set of EF, resulting in a spatially representative characterization of wildfire CO_2 emissions and their temporal evolution in China.

Table 4 The uncertainty estimation of wildfires CO_2 emissions from 2001 to 2022.

Year	Forest	Shrub	Grassland	Cropland	All types
2001	(-38%, 72%)	(-35%, 18%)	(-28%, 62%)	(-49%, 39%)	(-39%, 62%)
2002	(-35%, 68%)	(-34%, 16%)	(-24%, 47%)	(-49%, 34%)	(-39%, 54%)
2003	(-39%, 74%)	(-34%, 15%)	(-35%, 65%)	(-51%, 47%)	(-39%, 66%)
2004	(-36%, 69%)	(-37%, 22%)	(-15%, 58%)	(-50%, 40%)	(-39%, 57%)
2005	(-31%, 58%)	(-33%, 14%)	(-18%, 57%)	(-54%, 45%)	(-41%, 47%)
2006	(-30%, 56%)	(-32%, 12%)	(-18%, 62%)	(-56%, 47%)	(-46%, 48%)
2007	(-29%, 54%)	(-32%, 13%)	(-13%, 48%)	(-53%, 34%)	(-40%, 41%)
2008	(-50%, 106%)	(-42%, 29%)	(-39%, 67%)	(-52%, 43%)	(-50%, 93%)
2009	(-38%, 74%)	(-39%, 26%)	(-20%, 56%)	(-51%, 35%)	(-42%, 54%)
2010	(-37%, 73%)	(-45%, 34%)	(-15%, 82%)	(-59%, 50%)	(-48%, 56%)
2011	(-36%, 68%)	(-36%, 19%)	(-23%, 53%)	(-51%, 42%)	(-44%, 52%)
2012	(-35%, 66%)	(-36%, 18%)	(-27%, 57%)	(-58%, 44%)	(-52%, 47%)
2013	(-35%, 69%)	(-33%, 14%)	(-19%, 44%)	(-48%, 34%)	(-43%, 42%)
2014	(-40%, 79%)	(-36%, 19%)	(-26%, 68%)	(-43%, 39%)	(-41%, 50%)
2015	(-40%, 76%)	(-39%, 25%)	(-35%, 53%)	(-44%, 43%)	(-42%, 53%)
2016	(-44%, 91%)	(-42%, 29%)	(-24%, 54%)	(-46%, 56%)	(-44%, 70%)
2017	(-40%, 76%)	(-37%, 21%)	(-37%, 57%)	(-45%, 59%)	(-43%, 62%)
2018	(-53%, 114%)	(-41%, 27%)	(-30%, 59%)	(-45%, 62%)	(-49%, 90%)
2019	(-43%, 83%)	(-34%, 16%)	(-36%, 50%)	(-49%, 72%)	(-45%, 74%)
2020	(-48%, 95%)	(-40%, 24%)	(-39%, 62%)	(-53%, 86%)	(-50%, 85%)

2021	(-45%, 89%)	(-38%, 21%)	(-28%, 53%)	(-57%, 98%)	(-53%, 92%)
2022	(-35%, 66%)	(-34%, 16%)	(-24%, 56%)	(-45%, 66%)	(-42%, 63%)

3.6 Comparison with other studies

We compared the wildfire CO_2 emissions estimates in this study with several global biomass burning inventories, including the Fire Inventory from NCAR (FINN2.5, FINN_VIIRS2.5) (Wiedinmyer et al., 2023); GFED5 (van der Werf et al., 2017), the Global Fire Assimilation System (GFAS version 1.2) (Kaiser et al., 2012), and the Quick Fire Emissions Dataset (QFED version 2.5) (Koster and Darmenov, 2015), as shown in Figure 13. While all inventories exhibited consistent interannual variability, the total emission magnitudes varied substantially. Our estimates were systematically lower than those from most global datasets and were closest to GFASv1.2. FINN2.5 reported the highest values among all inventories, likely due to its use of larger burned area inputs. By incorporating VIIRS active fire detections, FINN_VIIRS2.5 showed approximately 25% higher emissions than FINN2.5. We applied GFED5 burned area data to adjust MCD64A1 burned area estimates; however, our emissions remain lower than those from GFED, which may be attributed to differences in biomass assumptions. Biomass input remains a dominant source of uncertainty in fire emissions estimates. QFED2.5 adopted a top-down approach based on fire radiative energy (FRE), and typically yields higher emission estimates (Wiedinmyer et al., 2023; Yin et al., 2019).

We further compared our estimates with other studies in China (Table 5). For forest, shrub, and grassland fires, our CO_2 estimates were comparable to those reported by Zhou et al. (2017) and Li et al. (2024a), slightly higher than those of Jin et al. (2022), and lower than Yin et al. (2019). The lower values in Jin et al. (2022) may result from exclusive reliance on MODIS burned area data, whereas the higher values in Yin et al. (2019) stem from the use of the FRE-based method. Regarding cropland fires, remote sensing often fails to detect small-scale agricultural burning. Consequently, many studies have used statistical data to estimate emissions, based on assumed field residue burning percentages ranging from 10% to 80% (Gao et al., 2002; Huang et al., 2012; Li et al., 2024b; Wang and Zhao, 2008; Yan et al., 2006; Yang et al., 2008; Zhou et al., 2017). The cropland fire CO_2 emissions estimated by the method based on burning proportion are generally higher than those calculated by the satellite remote sensing monitoring method adopted in this study.
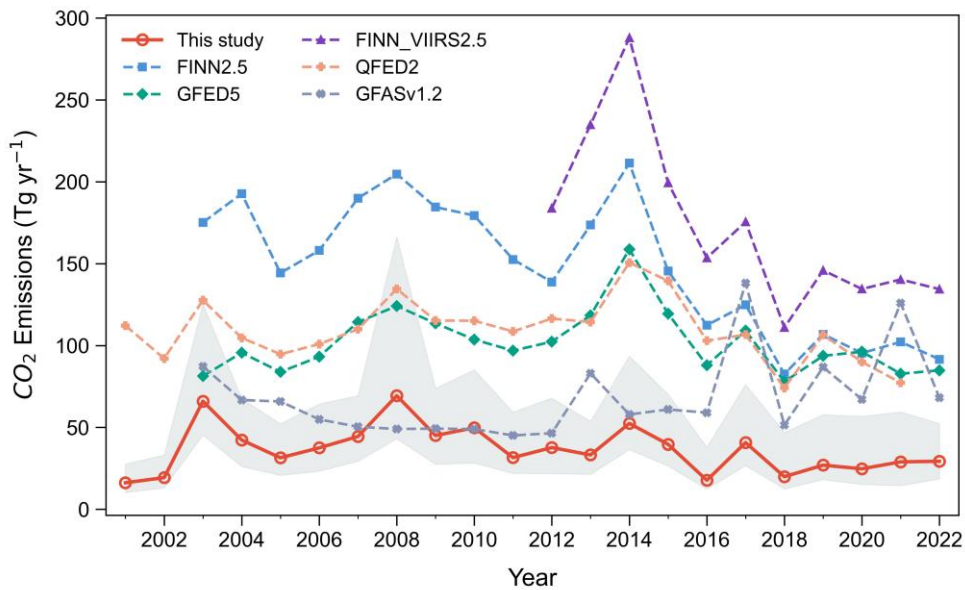
Figure 13: Comparison of wildfires CO$_2$ emissions in China from multiple global inventories (2001–2022).

Table 5 Comparison of wildfires CO$_2$ emissions estimates in China from previous studies(Tg).

Reference	year	region	Forest	Shrubland	Grassland	Cropland	All types
Wang and Zhao. (2008)	2006	China	-	-	-	154.5	-
Huang et al. (2012)	2006	China	-	-	-	68	-
This study	2006	China	-	-	-	26.3	-
Zhou et al. (2017)	2012	China		10.1	0.7	207.3	-
This study	2012	China		8.0	2.4	35.9	-
Yin et al.(2019)	2003-2017 (mean)	China	40.8	1.2	14.1	35.3	91.4
This study	2003-2017 (mean)	China	23.1	4.0	0.9	21.7	49.7

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Reference	Period	Region					
Jin et al.(2022)	2001-2019 (mean)	China		15.2		-	-
This study	2001-2019 (mean)	China		22.2		-	-
Li et al.(2024a)	2001-2020 (mean)	Heilongjiang	3.9	-	0.07	13.2	-
This study	2001-2020 (mean)	Heilongjiang	4.7	0.3	0.3	5.0	-

The burning of agricultural straw in China is a long-standing phenomenon, where burning straw is a traditional method for farmers to deal with waste straw after harvest. In recent years, the frequent occurrence of haze weather has seriously impacted people's production and life. Consequently, the government has introduced multiple policies to strengthen air quality and straw management. Since 2012, following the implementation of policies for air pollution prevention and control, CO_2 emissions from cropland fires have decreased (Fig. 7d). However, some provinces, such as Heilongjiang and Jilin, have had higher emissions since 2012 and are on an upward trend (Fig. 7d). In the northeastern region, a large amount of straw is used as the primary non-commercial energy source, leading to serious straw burning issues. Cropland fires in Northeast China mainly occur during the harvest and crop sowing seasons, with peak burning periods in October-November and March-April. Although China has recently prohibited open-air straw burning, this phenomenon persists, indicating that crop straw remains the primary fuel and waste of rural residents. More research is needed to develop new solutions for the sustainable utilization of crop straw in the northeast region, which may help achieve the dual goals of improving air quality and mitigating climate change.

This study holds great significance for atmospheric pollution control management. First, the high spatial resolution and long time series of wildfire CO_2 emissions provide accurate input data for simulating the effects of wildfires on air quality, climate, and human health. This helps to gain a deeper understanding of the impact mechanism of wildfires on the atmospheric environment, providing a reliable foundation for related research. Second, this research has a direct impact on global climate governance. The natural process of carbon emissions from wildfires is essential to the global carbon cycle, with prominent human intervention and control properties. Reducing wildfire carbon emissions is also a potential means of reducing global carbon emissions. However, the current international assessment and national emission reduction responsibilities do not include wildfire carbon emissions or consider measures such as reducing wildfire frequency and intensity through wildfire management. By accurately assessing CO_2 emissions from wildfires, governments worldwide can better set CO_2 reduction targets, take corresponding response measures, and contribute to the global response to climate change.

4 Conclusion

This study developed a comprehensive inventory of wildfire CO_2 emissions across China from 2001 to 2022, capturing significant spatiotemporal variations among different vegetation types. Results showed that cropland and forest fires were the

primary contributors to national wildfire emissions. Forest and shrub fire CO_2 emissions exhibited a declining trend, grassland fire CO_2 emissions remained relatively stable, and cropland fire CO_2 emissions showed an increasing trend. GTWR analysis revealed that shrub fire CO_2 emissions exhibited the highest predictive performance ($R^2 = 0.87$), with climatic factors (particularly temperature and humidity) being the main influencing factors, and limited temporal variation. In contrast, forest and cropland fire CO_2 emissions were significantly influenced by the spatiotemporal heterogeneity of both climatic and socioeconomic factors. Grassland fire CO_2 emissions exhibited the lowest model explanatory power ($R^2 = 0.31$), suggesting that their emissions may largely depend on drivers not included in the current model.

Our findings underscore the critical role of policy interventions in shaping wildfire emissions in China. The observed declines in most regions aligned with the implementation of national fire control and air pollution reduction programs. However, northeastern China remained an exception, with cropland fire CO_2 emissions continuing to increase in recent years. This trend highlighted the limitations of blanket burning bans and the necessity of adaptive fire management. Although forest fire CO_2 emissions had been reduced through strengthened fire prevention measures, northeastern China remained vulnerable to extreme fire events triggered by drought or lightning. Shrub fire CO_2 emissions, primarily driven by climatic factors, underscore the importance of strengthening early-warning systems.

Although wildfire emissions are classified as "natural disturbances" under IPCC guidelines for LULUCF and are often excluded from national emission inventories, the results demonstrated that these emissions were substantial and closely tied to policy and land management practices. The pronounced interannual variability and spatial heterogeneity suggested that future climate extremes, land-use changes, or fire policy adjustments could significantly alter regional carbon dynamics.

Compared with global emission inventories (GFED, FINN, QFED, GFAS), the estimates in this study were generally lower. Although remote sensing data might underestimate some cropland fires, this study characterized wildfire CO_2 emissions patterns in China by integrating multi-source burned area products, localized biomass data, and high-resolution land cover classifications. Future research should further refine burned area identification, optimize parameters such as emission factors and combustion efficiency, bridge observational gaps, and incorporate transboundary fire dynamics to ensure more comprehensive and accurate regional emission accounting.

Based on a bottom up approach and using MODIS fire products combined with emission factors of different wildfires (forest, shrub, grassland, cropland), the dynamic changes in CO_2 emissions in China from 2001 to 2022 were analyzed. Overall, during this period, the total CO_2 emissions from wildfires in China amounted to 693.7 Tg, with average annual emissions of 31.5 Tg. The CO_2 emissions from cropland and forest fires were relatively high, accounting for 46% and 32%, respectively; Shrub fire emissions accounted for 20%, while grassland fire emissions were the lowest, accounting for only 2%. The study revealed that emissions from forest and shrub fires exhibited a significant downward trend. In contrast, emissions from grassland fires remained relatively stable, and cropland fire emissions showed a noticeable upward trend. The emissions also showed different characteristics in different months, with generally lower emissions from all types of fires in July and August. Forest, shrub, and grassland fires had higher emissions in February, March, and April, and cropland fire emissions peaked in April, May, and June, possibly correlated with specific agricultural activities. Spatially, high CO_2 emissions were primarily

concentrated in the eastern regions of Heilongjiang and Inner Mongolia, accounting for 44% of the annual average total emissions. Northeast China was also identified as a high-confidence hotspot, indicating long-term high CO_2 emissions. Human activities significantly influence CO_2 emissions from cropland fires. Emissions negatively correlated with GDP (-0.52) and population density (-0.51). Various factors, such as accumulated sunshine hours (-0.41, p < 0.001) and the NDVI (-0.35, p < 0.001), mainly influenced emissions from forest and shrub fires, while temperature (-0.45, p < 0.001) primarily affected emissions from grassland fires. China's policy management has been crucial in reducing CO_2 emissions from wildfires. By accurately assessing CO_2 emissions from wildfires, governments worldwide can better set CO_2 reduction targets, take corresponding response measures, and contribute to the global response to climate change.

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Data availability

All the data supporting the findings of this paper can be accessed via the provided links or by requesting them using the contact information provided within those links. The China Land Use Land Cover Remote Sensing Monitoring Dataset (CNLUCC) is sourced from the Resource and Environment Science Data Registration and Publishing System (https://www.resdc.cn/, last access: 25 May 20254 June 2024). China's China's regional 250 m fractional vegetation cover dataset, China's China's regional 250 m normalized difference vegetation index dataset, and The Daily Meteorological Dataset of Essential Meteorological Elements of the China National Surface Weather Station (V3.0) are sourced from the National Tibetan Plateau/Third Pole Environment Data Center (https://data.tpdc.ac.cn/, last access: 25 May 20254 June 2024). MODIS-MCD64A1 burned area data are publicly available at https://lpdaac.usgs.gov/products/mcd64a1v061 (last access: 25 May 20254 June 2024). A 1 km harvesting area dataset is available at http://dx.doi.org/10.17632/jbs44b2hrk.2 (last access: 25 May 20254 June 2024). The FireCCI51 burned area product is publicly available from the European Space Agency Climate Change Initiative (ESA CCI) at http://cci.esa.int/data (last access: 25 May 2025). The GFED500 product can be accessed via the GFED website at https://www.globalfiredata.org/ (last access: 25 May 2025). The LandScan 2020 Global Population Database is available at https://landscan.ornl.gov/ (last access: 25 May 2025).

Author contributions

The article was written with contributions from all the authors. Xuehong Gong and Yongming Han designed this study;

Xuehong Gong, Zeyu Liu, Jie Tian, and Qiyuan Wang collected and organized the data; Xuehong Gong analyzed the data and wrote the original article with contributions from Zeyu Liu, Yongming Han, Guohui Li, and Zhisheng An. Zeyu Liu, Jie Tian, and Qiyuan Wang assisted with the submission of the article. All the authors have given approval to the final version of the article.

Competing interests

The contact author has declared that none of the authors has any competing interests.

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