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Analysis of Fire Scars Spatiotemporal Distribution and Carbon Emission in the Southeast Siberia Permafrost Degradation Area

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Abstract

Affected by climate change and other factors, global fires occur frequently, and the fire burning area in the high latitude permafrost region with low temperature is gradually expanding. The occurrence of fire will cause a large amount of carbon to be released into the air, which will further exacerbate global climate change. Through the fourth edition of the Global Fire Emissions Database (GFED), this paper analyzes the burning area and carbon emissions in the permafrost region of southeast Siberia from 1997 to 2020. The results show that the global carbon emissions from fires are mainly grassland and shrub fires, agricultural waste burning, northern forest fires, and tropical forest deforestation and degradation. The changes of grassland and shrub fires are relatively stable, and the burning area of agricultural waste has decreased, while the northern forest fires, especially in the northern North America and the Siberian permafrost region, have increased and increased rapidly in recent years. Further analysis of southeast Siberia shows that the fire burning area in southeast Siberia is mainly concentrated in spring (March to May) and autumn (September to November), of which the fire burning area in spring (March to May) is the largest, and the fire burning area in spring is 3.5 times of that in autumn. The gradually rising air temperature and gradually thawing carbon will become an important driving force of north forest fires. The occurrence of fire will further form positive feedback on climate change by affecting soil microorganism and soil structure, etc. Therefore, for sensitive areas such as southeast Siberia permafrost degradation area, targeted fire warning and management mechanisms need to be established to effectively reduce the risk of wildfire.

Keywords

Southeast Siberia; Permafrost Degradation Area; Fire Scars; Carbon Emissions.

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1. Introduction

With the intensification of global warming, fires occur frequently everywhere. The occurrence of fires will lead to the release of particulate pollutants, as well as a large amount of carbon dioxide, nitrogen oxides, etc. into the air. The release of these substances will not only threaten the local air quality and life safety, but also further exacerbate global climate change. At present, there are millions of hectares of forest burning in the world every year, the ecological balance has been seriously damaged, the high cost of forest fire fighting has been consumed and casualties have been caused. In addition, forest resources are important renewable resources and the basis for ensuring biodiversity. Therefore, controlling the occurrence of fire and strengthening the protection of forest resources have an important role in improving the environment and promoting the development of forestry economy[1-5].

Forest fires burn 5-20 million hectares of northern forest every year, and up to 80% of the northern forest area is located in the polar permafrost zone[6-8]. About half of the global soil carbon is located in the permafrost of the northern hemisphere, but it is estimated that one quarter of the permafrost will be thawed by 2100 [9]. The carbon storage of the permafrost is estimated to be more than twice that of the atmospheric carbon pool (750PgC)[10], and the thawed permafrost will have a significant positive feedback on climate change by decomposing previously frozen organic matter and releasing greenhouse gases[11-13]. In the past two decades, in addition to the carbon released from the melting permafrost, the northern fires also released a large amount of carbon [14] in northern North America (60TgC year^{-1}) and Asia (124TgC year^{-1}). The carbon released by the northern fires can accelerate global warming, and play a positive feedback role between atmospheric carbon accumulation and Arctic warming [15-16]. The northern fires show obvious spatial distribution, including two major regions in Central Asia and southeast Siberia. Northern wildfires usually occur in summer, because wildfires in high latitudes are restricted by temperature for the rest of the year [17-19].

The study on the number and burning area of wildfires in Siberia found that the number and burning area of forest fires have increased in recent decades ($p<0.05$). It is found that there is a significant correlation between forest fire, burn area and temperature (r=0.5) and drought index (standard precipitation evapotranspiration index, SPEI) (r=0.43). In the larch forest along the section, the frequency of wildfire is closely related to the incident solar radiation (r=0.91) [19]. After the forest fire, the permafrost will further thaw, and the respiration rate of microorganisms after the fire is three times higher than that before the fire, greatly increasing the diffusion of CO_2, CH_4 and N_2O[20]. At the same time, the fire affected the water and heat conditions in the permafrost region. After the fire, the surface albedo was reduced, resulting in changes in the surface heat conditions, the thickness of the active layer was deepened, and the loss of organic carbon (SOC) and nutrients was accelerated. Therefore, after the fire, the entire forest system needed more than one century to recover from the disturbance[21]. In order to further study the fire occurrence and carbon emission in the permafrost region of southeast Siberia, we use the fourth edition of the fire emission database (GFED) to quantify the fire emission patterns in the permafrost region of southeast Siberia from 1997 to 2020 and describe the fire carbon emissions in different regions.

2. Data Source and Regional Distribution

The database model system is based on the Carnegie-Ames-Stanford method (CASA) biogeochemical model. Some modifications have been made to the previous version, and higher quality input data sets have been used. Major upgrades include new burning area estimates, including those caused by small fires. Revised fuel consumption parameterization optimized using field observations; Improve the representation of fuel consumption in the combustion landscape; The estimated fire severity can better reflect the continental differences in the

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combustion process between North America and northern Eurasia. With higher spatial resolution (0.25), data source http://globalfiredata.org/.

According to geographical location and climatic conditions, the world is divided into 14 regions, including: Boreal North America (BONA), Temperate North America (TENA), Central America (CEAM), Northern Hemisphere South America (NHSA), Southern Hemisphere South America (SHSA), Europe (EURO), Middle East (MIDE), Northern Hemisphere Africa (NHAF), Southern Hemisphere Africa (SHAF), Boreal Asia (BOAS), Central Asia (CEAS), Southeast Asia (SEAS), Equatorial Asia (EQAS) , Australia and New Zealand (AUST), as shown in Figure 1.

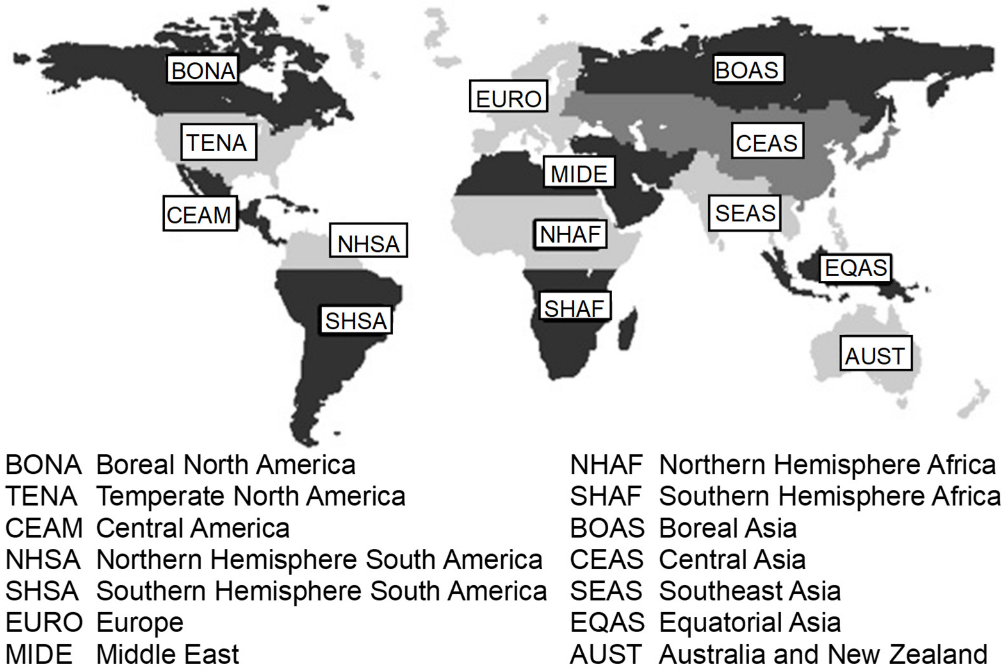

Figure 1. 14 regions in the world, data from Giglio et al [22] and Wander werf et al. [23]

3. Greenhouse Gas Emissions from Global Fire

The global large-scale combustion will release a large amount of carbon into the air. The release of these carbon will not only threaten the local air quality and life safety, but also further exacerbate global climate change. In addition, different combustion types and burning areas have different contributions to the emission of pollutants, so we give the carbon emissions of different combustion types and burning areas through the fourth edition of the Global Fire Emissions Database (GFED). Combined with the carbon emission image of MODIS from 1997 to 2020 (Figure 2), it can be seen that the carbon emission of combustion is consistent with the burning area as a whole, and the large areas of carbon emission caused by fire are concentrated in the Boreal North America (BONA), Southern Hemisphere South America (SHSA), Northern Hemisphere Africa (NHAF), Southern Hemisphere Africa (SHAF), Boreal Asia (BOAS), Southeast Asia (SEAS), Australia and New Zealand (AUST). The carbon emissions from natural forest/grassland fires, anthropogenic biomass and fossil fuel combustion are the important impact factors of current global change, second only to greenhouse gases. Correct assessment of the historical changes of carbon emissions and the contribution of anthropogenic emissions is an important basis for accurate assessment of the impact of human activities on climate and environmental change and reasonable formulation of emission reduction policies.

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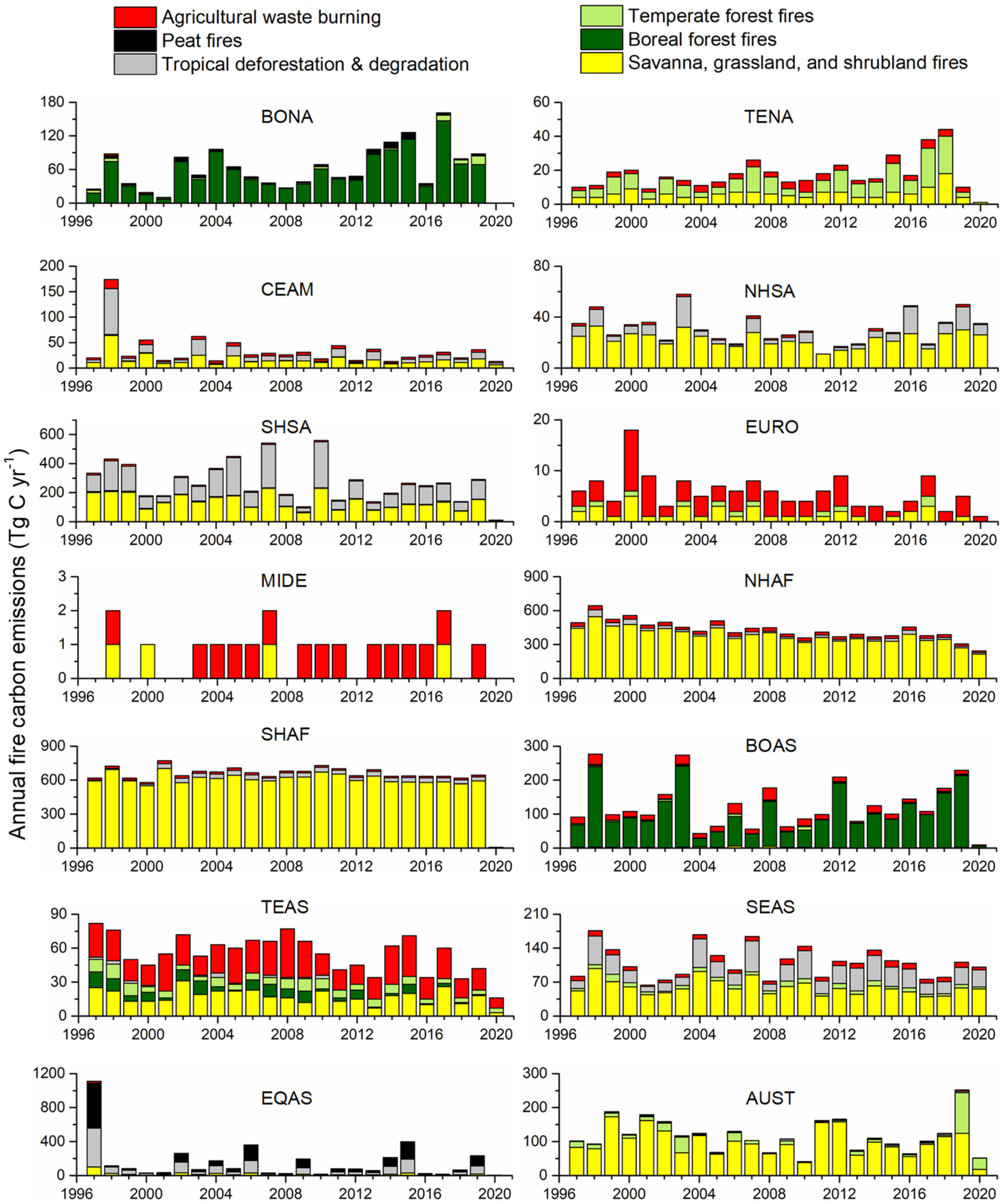

Figure 2. Carbon emissions from GFED4s fires in different regions and sources each year

According to Figure 2, it can be seen that the global fire carbon emissions are mainly savanna, grassland and shrubland fires, agricultural waste burning, boreal forest fires and tropical deforestation and degradation. However, savanna, grassland and shrubland fires have changed relatively little in recent years, and the agricultural waste burning has decreased, while boreal forest fires, especially in Boreal North America (BONA) and Boreal Asia (BOAS), have increased and increased rapidly in recent years. Among them, the carbon emissions in Boreal North America (BONA) are mainly from north forest fires, contain some peat fires and temperate forest fires. The overall emissions are increasing year by year. In 2017, the carbon emissions were the largest, with the total carbon emissions reaching 161Tg C year^{-1}; Boreal Asia (BOAS) carbon emissions are mainly caused by north forest fires, and contain some agricultural waste burning and peat fires. After 2003, the overall emissions are increasing year by year. In 1998, the carbon emissions were the largest, with the total carbon emissions reaching 274Tg C year^{-1}.

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4. Fire and Gas Emission in Southeast Siberia

The above study shows that, in addition to the low latitude regions with higher temperatures, Siberia in northern Asia and the high latitude permafrost regions in northern North America also have large burning areas, and the fires in this part of the region are mostly forest fires. Therefore, in order to study the fire occurrence in the permafrost region, we select the permafrost region in southeastern Siberia as the study area (115°E-145°E, 45°N-55°N), as shown in Figure 3.

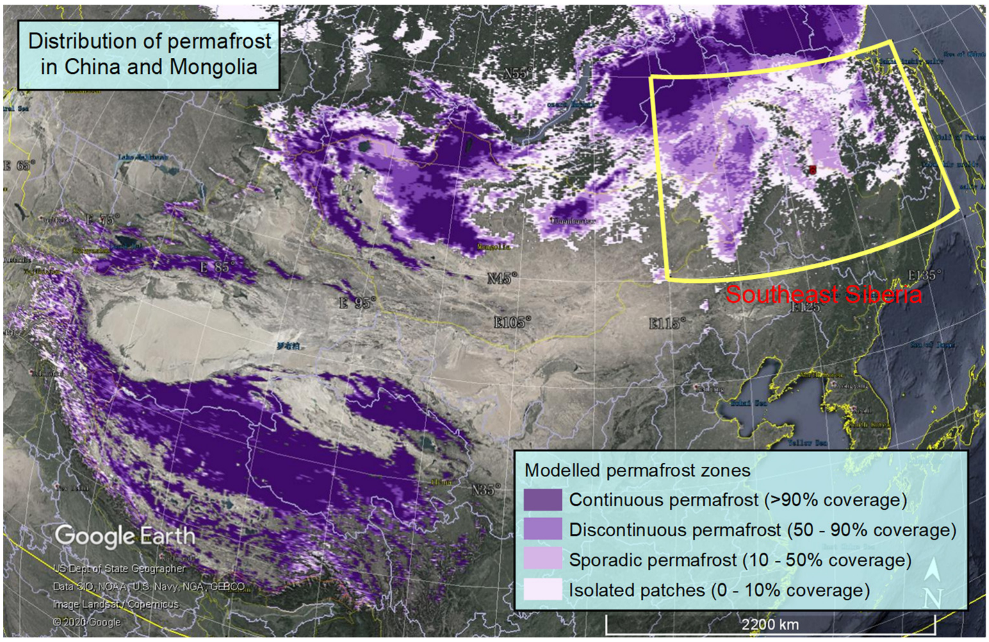

Figure 3. Distribution of permafrost in southeast Siberia and location of the study area, data from Jaroslav O. et al. (2019) [27].

The study area is located in the high-latitude permafrost region of southeast Siberia at the southern edge of the Eurasian continental permafrost region, and is in the transition zone between the cold temperate zone and the middle temperate zone. Affected by the high and low pressure and monsoon alternation in the inland and the sea, the annual average temperature is low, and the annual range is large, showing the continental monsoon climate. Due to the control of Siberian high pressure in winter, stable inversion layer is widely distributed in the region, which has an important impact on the development and regional distribution of frozen soil. The permafrost in the region is mainly distributed in the valley, the foot of the mountain, the shady slope and other places, with the typical distribution characteristics of "Xing'an-Baykal type" permafrost [26]. The thickness of frozen soil ranges from several meters to tens of meters to 50~75m, even more than 100m. Due to the comprehensive impact of regional geological conditions, climate change and human activities, the permafrost is being degraded and distributed in continuous, discontinuous, sporadic and even isolated patches from north to south (Figure 3)[27].

According to the air temperature change curve of 11 national meteorological stations in the study area from 1960 to 2019, it can be seen that the air temperature in the study area has an overall upward trend (Figure 4). In addition, according to the freezing index, freezing number and melting index change curve (Figure 4) near the Sunwu National Meteorological Station in the study area, it is found that the surface melting index has increased significantly since 2004, and the surface freezing index and ground freezing number have shown a significant downward

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trend, and have declined in a precipitous manner between 2004-2006. It is inferred that the remaining shallow permafrost in the south of the study area has been completely thawed.

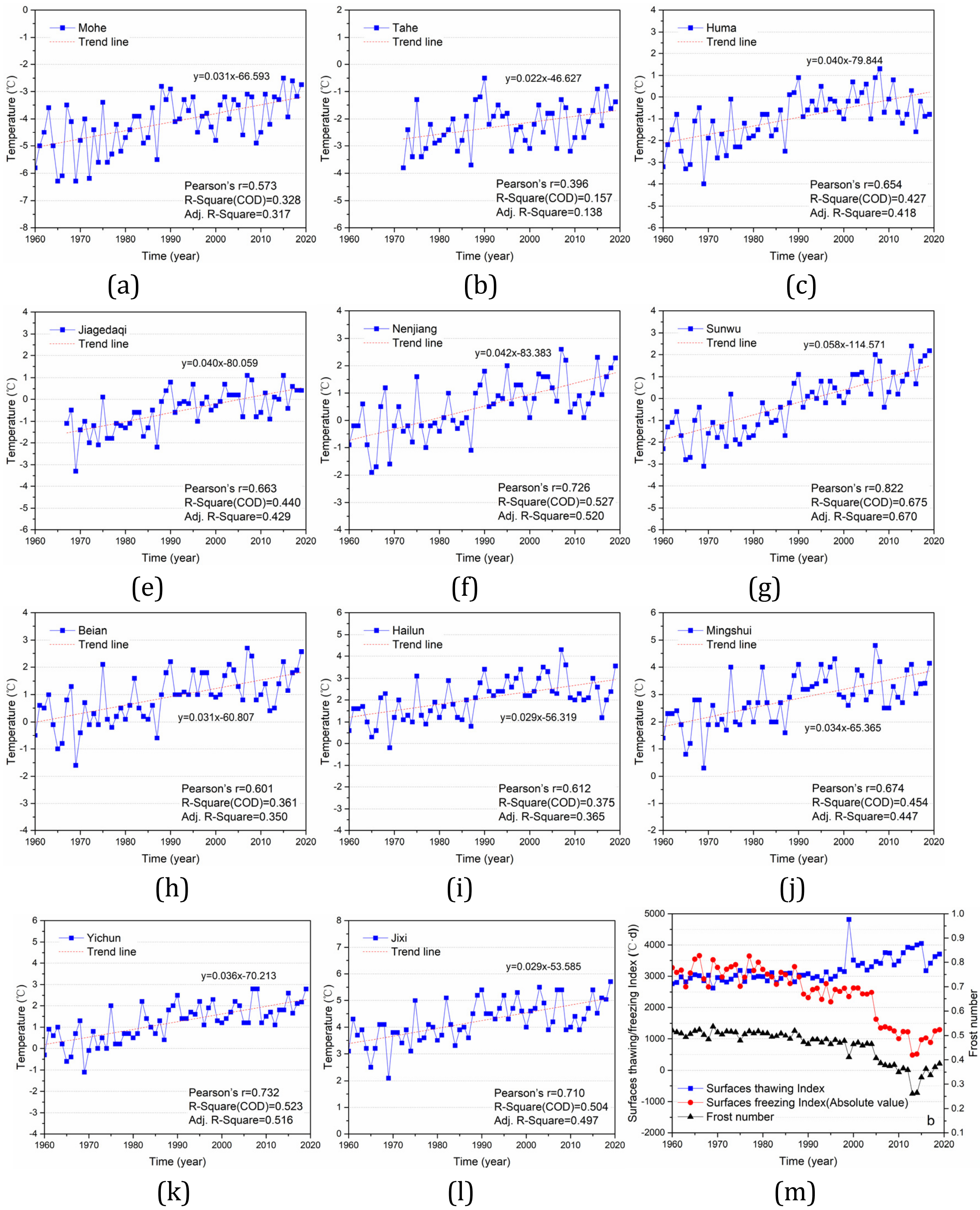

Figure 4. Changes of air temperature, ground freezing (melting) index and ground freezing number in the study area from 1960 to 2019

The study area is located at the southern edge of the Eurasian permafrost region. There is a large area of permafrost and the degradation rate is gradually accelerating. The causes of fire in the permafrost region are very complex, including human factors, lightning, and flammable methane gas released from the melting of the permafrost layer. Figure 5 shows the change of burning area and monthly average burning area in the study area from 1997 to 2016. It can be seen that the burning area of wildfire in the study area has decreased since 1997, reaching the

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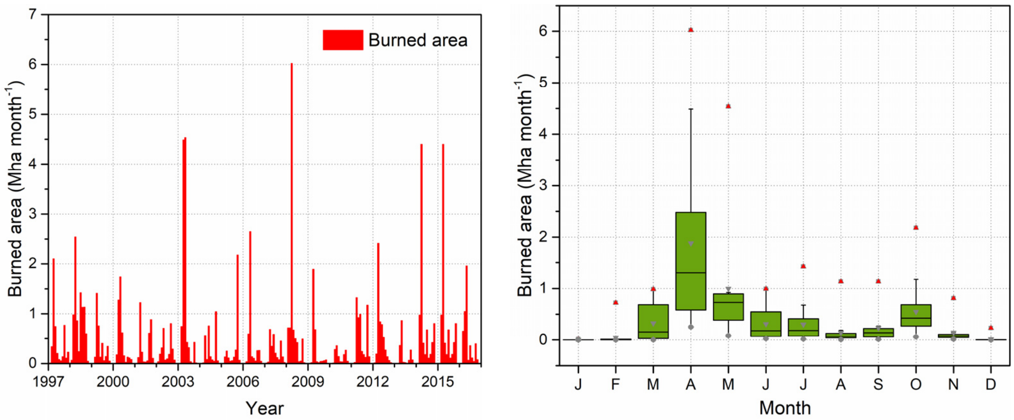
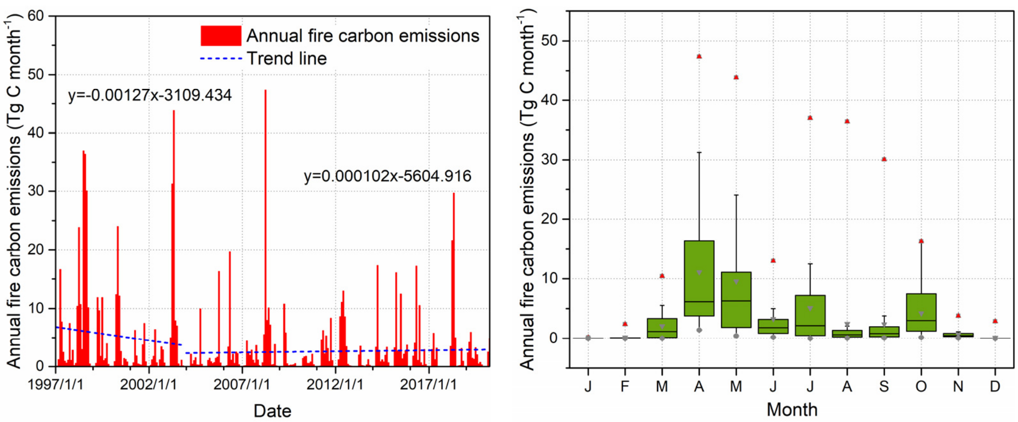
minimum value of 2.776Mha year^{-1} in 2002 (Figure 5a,). However, fire area has increased rapidly since 2003, and the overall burning area of wildfire has increased in recent years.



(a) (b)

Figure 5. Change of burning area and monthly average area after burning in the study area from 1997 to 2016

The burning area in southeast Siberia is mainly concentrated in spring (March to May) and autumn (September to November) (Figure 5b). The burning area in spring (March to May) is the largest, with an average value of 1.067Mha month^{-1}, and the monthly maximum value is 6.024Mha month^{-1} in April; The average value of fire burning area in autumn (September to November) is 0.308Mha month^{-1}, and the maximum value in October is 2.178Mha month^{-1}, of which the burning area in spring is 3.5 times that in autumn. The laws of carbon emissions caused by fire are consistent with the laws of fire occurrence. Since 1997, the carbon emissions of fire in the study area have decreased. reaching the minimum value in 2002, the minimum carbon emissions were 18.431Tg C year^{-1}. After 2003, the burning area of wildfire and the carbon emissions of fire have increased overall (Figure 6).



(a) (b)

Figure 6. Carbon emissions caused by fires in the study area from 1997 to 2016

From 1997 to 2016, the fire burning area in the permafrost region of southeast Siberia is gradually expanding. In addition to the southern region, the burning area is also gradually expanding to higher latitudes with lower temperature, which may be due to the increase of global temperature and the release of flammable methane gas from the thawing of frozen soil (Figure 7).

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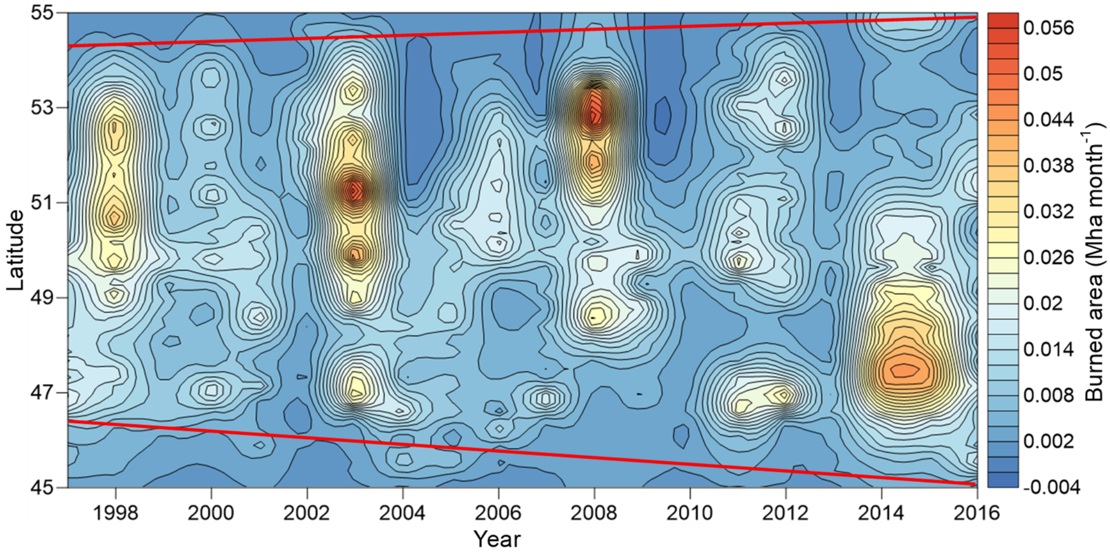

Figure 7. Change of burning area at different latitudes in the study area from 1997 to 2016

5. Conclusion

Influenced by global climate warming, natural drive and human activities, global fires occur frequently. Except for low latitude regions with high temperature, the fire burning area of high latitude permafrost regions with relatively low temperature is gradually expanding. The expansion of fire burning area leads to the gradual increase of global carbon emissions. The global carbon emissions from fires are mainly grassland and shrub fires, agricultural waste burning, northern forest fires, and tropical forest deforestation and degradation. grassland and shrub fires have changed relatively little in recent years, and the burning area of farmland waste has also decreased, while northern forest fires, especially in northern North America and Siberia, have increased and increased rapidly. Air temperature in the permafrost region of southeast Siberia is generally rising and the shallow permafrost is melting. With the gradual degradation of permafrost, the fire burning area in southeast Siberia has increased rapidly since 2003, and the two are positively correlated. In addition to the low latitude areas with higher temperatures, the fire burning area is expanding to the north high latitude permafrost areas with lower temperatures. In addition, the fire burning area in southeast Siberia is mainly concentrated in spring (March to May) and autumn (September to November). The fire burning area in spring (March to May) is the largest, with an average value of 1.067Mha month^{-1}, and the monthly maximum value appears in April, with 6.024Mha month^{-1}; The average value of fire burning area in autumn (September to November) is 0.308Mha month^{-1}, the maximum value in October is 2.178Mha month^{-1}, and the burning area in spring is 3.5 times that in autumn. The increase of fire burning area will further lead to the gradual increase of carbon emissions.

Acknowledgments

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