Spatial and temporal monitoring of wildfires in Golestan province using remote sensing data

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Abstract. Wildfires are one of the most significant factors of ecosystem change. Knowing the wildfire regime (frequency, intensity, and distribution pattern) is essential in wildfire management. This research aims to analyze the spatiotemporal pattern of wildfires in Golestan in 2001-2021 using MODIS data, burned area product (MCD64A1). For this purpose, the annual and monthly frequency, as well as the trend of wildfires based on types of forest, pasture, and crop cover, were statistically analyzed. The local Moran pattern analysis method and kernel density function were used to analyze the spatial dynamics of wildfire. The results showed that 18,462 wildfires occurred in Golestan, the highest of which was in 2010, with 2,517 wildfires (13.8%). The lowest number of wildfires, with only 57 events (0.5%), was in 2001. Based on the local Moran model results and the kernel density function, the wildfires' extent and intensity were greater in the plains and foothills to the south and southeast of Golestan. The lowest extent and intensity of the wildfire corresponded to the eastern parts of the province. The frequency of wildfires was higher in the hot period of the year (spring and summer). However, the period of occurrence of wildfire and the peak of wildfire changes in different uses. The wildfire zones in June were wider and more intense than in other months. The frequency and spatial extent of wildfires in agricultural lands from May to July, pasture lands in July, August, and September, and forest lands in November and December were more than in other months. Weather conditions play a significant role in the occurrence of wildfire in the forest lands of Golestan. The results of this research help understand wildfire risk areas and provide a scientific basis for predicting and controlling wildfires and reducing carbon emissions related to them.

Keywords: wildfire, Kernel density function, Moran's index, Modis, Iran.

1. Introduction

Wildfire is an unplanned, uncontrolled and unpredictable fire in an area of combustible vegetation that affects the earth's surface, atmosphere and human life (Bahadur Bhujel et al., 2022). Around 4 percent of the global forest burns every year (Bahadur Bhujel et al., 2022), which depends on various factors such as weather, type of vegetation and structure, fuel moisture, land use, and human activities (Nhongo et al., 2020). The Intergovernmental Panel on Climate Change states that climate change is often the dominant factor affecting large wildfires (Shi & Touge, 2022). Based on the results of various studies, climate changes will lead to changes in the frequency and behavior of wildfires in the future, which influencing terrestrial ecosystems composition, structure, and functioning (Ahmad et al., 2018; Varela et al., 2019; Seydai et al., 2020). Furthermore, wildfires play a significant role in generating CO_2 emissions, affects the function of carbon sinks of terrestrial ecosystems (Zhang et al., 2023). Catastrophic wildfires have increased all over the world in recent years. For example, destructive wildfires occurred in the western United States in 2020 and California in 2018 (Shi & Touge, 2022). Wildfires are currently the main cause of forest destruction in Mediterranean countries, which causes huge economic and ecological damage and human casualties (Serra et al., 2012). Wildfire the problem is common and no continent or country is an exception (Yeremenko et al., 2021). From 2008 to 2019, 12,925 fires were registered in Tanzania (Naftal et al., 2022). In 2019, wildfires burned 1.01 million hectares in Alaska, and massive wildfires occurred in Siberia, which were both driving extremely high temperatures (Shi & Tougo, 2022).

Also, wildfires have been frequented in the forests of northeastern Iran in recent years; for example, in 2010, more than 16,000 hectares of forest land in this area were destroyed in less than a month (Abdi et al., 2018). Wildfires have harmful effects on climate and human society. Natural or controlled (human) wildfires release significant amounts of carbon dioxide, carbon monoxide, and methane into the atmosphere, significantly worsening air quality and endangering human health (Zheng B. et al., 2021; Fan et al., 2023). It can also lead to deforestation or other changes in vegetation structure (Senande-Rivera et al., 2022). In addition to natural causes, human factors also play a dominant role in causing wildfire, which, according to studies and reports, are ten times more than natural causes (Bahadur Bhujel et al, 2022). Most human-caused wildfires are caused by behavioral issues, including carelessness or inattention by hikers, travelers, and litter burners (Gonzalez-Olabarria et al., 2015; Lewis et al., 2015). Human factors such as housing density, population density, and road networks have important effects on the spatial distribution of wildfires (Miranda et al., 2012). Based on the research results of Guo et al. (2015) in the northern forests of China, the distance between forests and human settlements or roads plays an important role in causing wildfires. Also, the distance of the forest from the road has a lot to do with the severity of wildfire occurrence in the forests of Golestan, located in the northeast of Iran (Abdi et al., 2018). Knowledge of the wildfire regime (frequency, intensity, and distribution pattern) is important in forest wildfire management. For example, spatio-temporal wildfire patterns can provide important information in understanding wildfire behavior and regime (Nhongo et al., 2020). Therefore, to create wildfire prevention and management strategies, it is necessary to understand spatial and temporal patterns of wildfires, that is, to know where, when, and why they occur (Nhongo et al., 2020; Zhang et al., 2023). The temporal and spatial distribution of wildfire occurrences in the forests of Nepal has indicated that wildfire increased from 2001-2021, and the forests of the Tarai-Sivalik region in Sudorpashim district and Madesh province are at risk of occurrence of wildfires (Bahadur Bhujel et al., 2022). Arisanty et al. (2021), by using the geographic information system (GIS), investigated the spatial and temporal patterns of burned areas in Indonesia and determined that the highest number of wildfires occurred in areas with low to medium vegetation density, corresponding to peatland areas. In recent years, the availability of satellite data with different spatial, temporal, and spectral resolutions has made it possible to detect and monitor active fires (Nhongo et al., 2020). Based on the research results of Alinai et al. (2021) regarding the temporal and spatial analysis of wildfire in Lorestan province using the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor products, it was determined that more than 70% of wildfire in Lorestan occurred in June and July. Nhongo et al. (2020) using MODIS data, active fire product (MCD14ML), and burned area product (MCD64A1), examined the spatiotemporal patterns of wildfires in Niasa located in Mozambique and came to this conclusion. They found that 20,449 wildfires occurred in forest lands, the highest rate in 2015. Villar-Hernández et al. (2022), using MODIS sensor data, determined the spatiotemporal changes of wildfires in Oaxaca, Mexico and they showed that wildfires have increased by 42.2% in the last two decades. If this trend continues, hundreds of hectares of new forests and their biodiversity will be destroyed in the coming decades. Also took the analysis of spatial and temporal changes in the occurrence of wildfires from 2003 to 2016 in the state of Amazonas located in Brazil, based on the AQUA satellite data, showed that about 83% of the wildfires in the wild areas occurred in August, September, and October (White, 2018).

Being located in West Asia, Iran is one of the arid and semi-arid regions of the world, which has the necessary climatic conditions for the occurrence of wildfires in its forests and pastures (Kalbali et al., 2021; Shokouhi et al., 2023; Alinai et al., 2021). In the forests of Golestan, compared to other regions of the country, there are more intensity, size, power, and extent, in such a way that more than 1250 cases of wildfire in an area of more than 10000 hectares in the last 20 years (1990 to 2010) occurred in this province, which has the highest percentage compared to other parts of the country (Mirdeilami et al., 2014). With the increasing trend of wildfires and the resulting damages, it is necessary to develop methods to deal with them (Parnian et al., 2021). Considering the ecological importance of forests and pastures in Golestan and the adverse climatic effects of recent years on this area (such as droughts and strong winds), the risk of wildfire is expected to be a threatening factor (Meftahhalaghi & Ghorbani, 2015; Silakhori et al., 2022). Considering the mentioned cases, to predict and adequately manage this phenomenon, it is necessary to monitor the spatial and temporal pattern of wildfire occurrence in the natural lands of this province.

2. Materials and methods

Golestan province is located in northeastern Iran and on the southeastern coast of the Caspian Sea. This province is located between 36°25' to 38°8' north latitude and 53°50' to 56°18' east longitude (Abdi et al., 2018). Due to its geographical location and topography, Golestan has a wide variety of climates. The weather conditions in this province vary from hot, dry, and semi-arid climates in the border zone and Atrak watershed, to cold and semi-humid in the northern parts, to moderate to hot and semi-humid in the southern and western regions (Asadi Oskouei et al., 2022). The average annual rainfall in this province is about 450 mm, 70% of which occurs in non-agricultural seasons (October to April). The amount of rainfall in the southern and southwestern regions of the province is about 700 mm, and in the northern and border areas is about 200 mm (Hasanalizadeh et al., 2015). The average annual temperature values fluctuate between 17.9 and 18.5 degrees Celsius (Sharifnrjad et al., 2021). The average evaporation varies from 800 mm in the southern and highland areas of the province to 2000 mm in the border areas in the north (Ayouzi et al., 2018). About 18% of the area of Golestan is covered with forest, and the forest areas of this province are among the tourist areas of the country (Pahlavani et al., 2020). Figure 1 shows the geographical location and land use of Golestan. According to Figure 1, there is a variety of vegetation, including farmlands, bushes, and forests from the north to the south of the province. A significant part of the northern lands consists of poor to good pastures. Towards parts of the foothills and also the border between the foothills and the Gorgan River is covered with agricultural lands. The largest forests are located in the south and southeast of this province.

In this research, to monitor wildfires in Golestan, the burned surface data from the burned surface product, the monthly product MCD64A1, was used in the statistical period of

2001-2021. The MODIS sensor on two satellites, Terra and Aqua, can control and monitor wildfires and is currently an essential source of global data on fire locations and burned areas (Giglio et al., 2018). This sensor is fully automatic in wildfire detection and can generate global daily wildfire information, including geographical coordinates of wildfire, date and time of fire occurrence, reliability coefficient, etc. MCD64 is the last product of MODIS burnt surface products. MCD64 uses active fire observations to analyze the statistical characteristics of burn-related changes and uses Bayesian probability testing methods to classify burned or unburned grid cells globally (Nhongo et al., 2020; Giglio et al., 2018). The MCD64A1 product has a spatial resolution of 500 meters. It has improved the detection of burned areas compared to previous products (specifically, in better detecting small fires and adapting to different regional conditions in multiple ecosystems). The MOD64 product uses a burn-sensitive vegetation index (VI) to create dynamic thresholds that are applied to combined Terra and Aqua data (Nhongo et al., 2020; Fan et al., 2023; Giglio et al., 2018)

In environmental analysis, the spatial-temporal distribution pattern of wildfires and the trends governing them are essential for proper planning and management (Fan et al, 2023). This research used spatial statistics analysis methods, including the local Moran pattern analysis method (Local Indicators of Spatial Association), Kernel Density function was used. Moran's index (I) shows the degree of spatial autocorrelation between adjacent points and the way of data distribution (cluster or random). In Moran's statistic, positive values (between 0 and 1) and negative values (between 0 and -1) indicate direct and inverse correlation, respectively. In the local Moran method, the significance of the index must be checked first; Thus, in cases where the P-Value was very small and the calculated Z value was enormous, the null hypothesis of no spatial clustering is rejected. Moran’s, I index is a general statistic. It does not provide the possibility of evaluating the regional structure of spatial autocorrelation, identifying local spatial clusters and regions contributing to the overall spatial autocorrelation. Therefore, the local LISA was used to investigate the pattern governing the wildfire spread in Golestan. Anselin local Moran's index is one of the valuable tools for showing the statistical distribution of phenomena in space. It shows where high or low amounts of phenomena are clustered in space and which complications have. The amounts are very different from the complications around them. The local Moran statistic is obtained as follows (Eq. 1):

$$Ii = \frac{xi-x}{s_i^2} \sum_{j=1.j\neq}^{n} wi.j(xj-x) \rightarrow s_i^2 = \frac{\sum_{j=1.j\neq 1}^{n}(xj-x)^2}{n-1} \quad (1)$$

where x_i is the characteristic of complication i, x is the average of the corresponding characteristic and w_i, j is the spatial weight between complication i and j, and n is the total number of complications (Asadi & Karami, 2017; Parchomenko & Borsky, 2018).

The kernel density function method is one of the analyzes of spatial statistics analysis, which is used under the title of density estimation for linear and point effects. This analysis is considered one of the best methods for identifying hot spots, which can be used to identify places with high wildfire risk. The kernel density estimation method, introduced by Rosenblatt (1956), has attracted considerable attention in non-parametric probability density estimation. Kernel density estimation is a popular method for one-dimensional and two-dimensional data analysis. This method can quickly visually identify hotspots from an extensive database, thus provide a satisfactory statistical output. In this method, the areas closer to the location of the wildfire will have more weight than other areas, resulting in a more even distribution of values. In such a way, the area close to the occurrence is darker and has the highest risk of wildfire, and the further away from it, the brighter it is and has less risk. In other words, the areas with a higher density of wildfires are much more colorful than those with less frequent ones (Seydai et al., 2020; Zeynali et al., 2015). Kernel point density is defined as follows (Eq. 2)

$$\hat{f}(x) = \frac{1}{nh^2} \sum_{i=1}^{n} k \left\{\frac{x-x_i}{h}\right\} \tag{2}$$

where: n is the number of observed points, h is the bandwidth, K is the kernel function, x is the coordinate vector that shows the location of the estimated point, and x_i is the coordinate vector of i that shows each observed point about the estimated value (Nhongo et al., 2020).

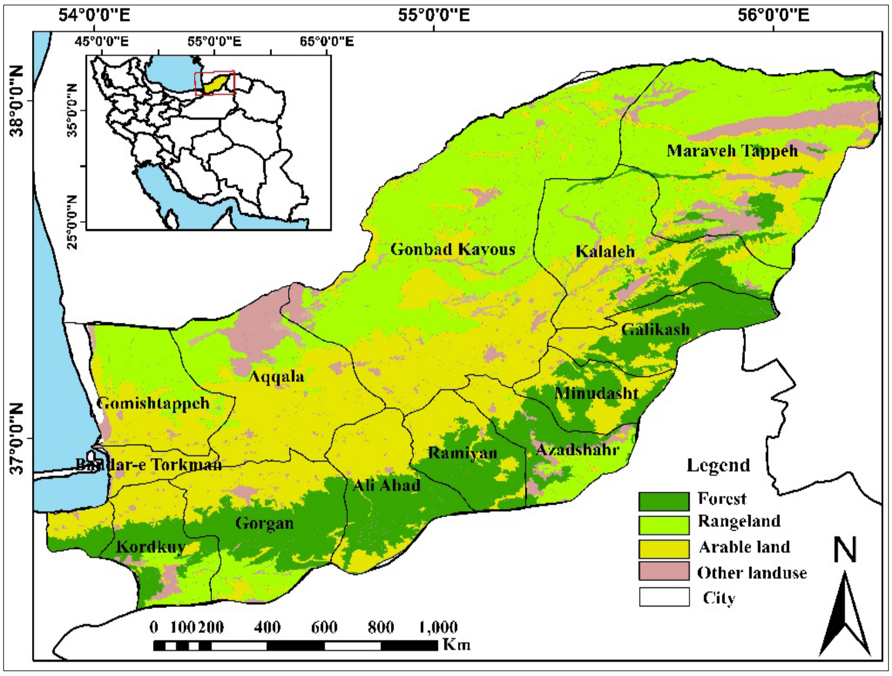

Figure 1. Geographical location of the study area

Also, the distribution of wildfire points in different agricultural, pasture, and forest uses at different altitudes and slope levels was investigated. The slope map of the area was obtained based on the Digital Elevation Model (DEM) and classified into five slope classes, including 0-15, 15-25, 25-35, 35-45, and 55-45 degrees.

3. Results

3.1 Monitoring wildfire on monthly time scale

Examining the distribution of wildfires in different seasons and months showed that summer (June to August) had the highest number of this event, with 54% (Fig. 2). After summer, spring, and autumn, they accounted for 20.8% and 18% of wildfire, respectively. The lowest number of this event, with 6.7%, was related to winter, especially in January and February.

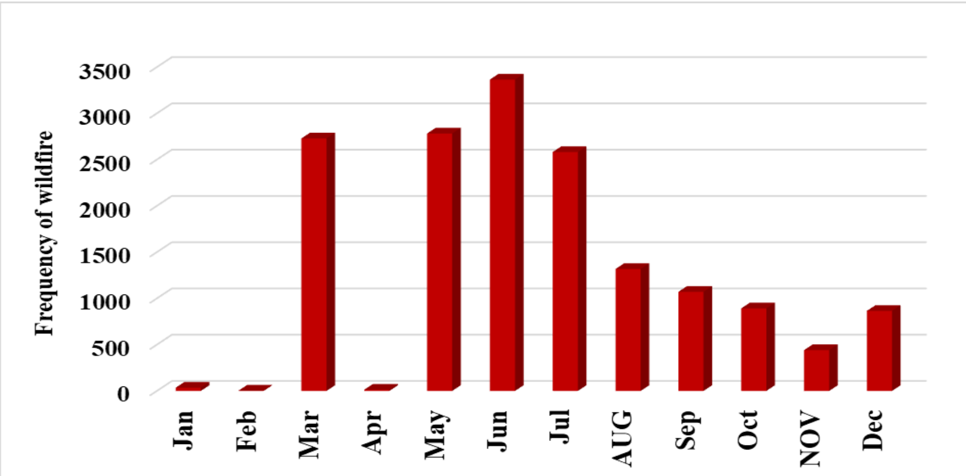

Figure 2. The number of wildfires in the seasonal time scale in Golestan in the statistical period of 2001-2021

The occurrence of wildfires in agricultural, pasture, and forest lands is shown in Figures 3, 4, and 5, respectively. According to Figures 3, 4, and 5, the wildfire zones in June are wider and more intense than in other months and cover significant parts of the region, especially in agricultural lands. According to Figure 3 the extent and frequency of wildfires in agricultural and pasture lands in the hot months of the year (May, June, July, and August) have been far more than in other months. Wildfires occurred from May to July, mainly in significant parts of agricultural lands to the central areas between the foothills and Gorgan River (Fig. 3).

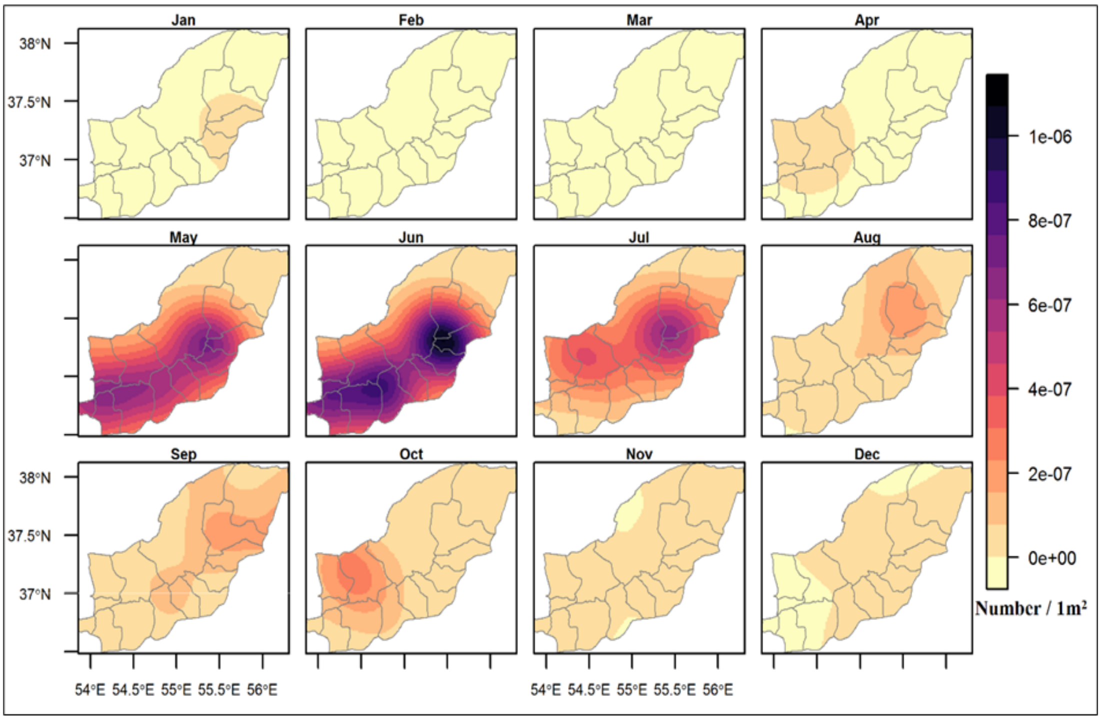

Figure 3. Spatial distribution of wildfire density in agricultural lands on monthly time scale in the statistical period of 2001-2021

The maximum core and spatial extent of wildfires in pasture lands were related to July, August, and September, which corresponded to the pasture lands of the northern and northeastern parts, especially in Kalaleh and Gonbadkavus (Fig. 4).

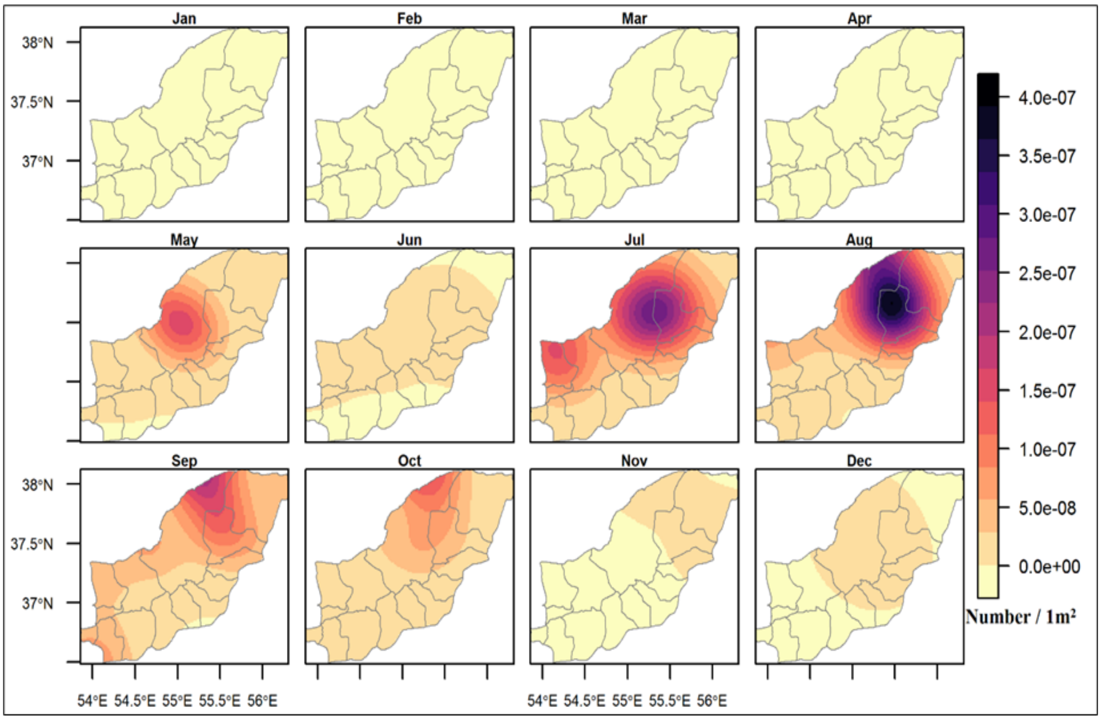

Figure 4. Spatial distribution of wildfire density in pasture lands on monthly time scale in the statistical period of 2001-2021

According to Figure 5, the extent and core of the maximum wildfire has shifted towards the cold period (November and December) to the forest lands in the southern and southeastern parts. The distribution of the extent and frequency of wildfires in December were more than in other months, which mainly corresponds to the southern areas located in the forest part of Galiksh and Minodasht and parts of Ramyan and Aliabad (broad-leaved trees

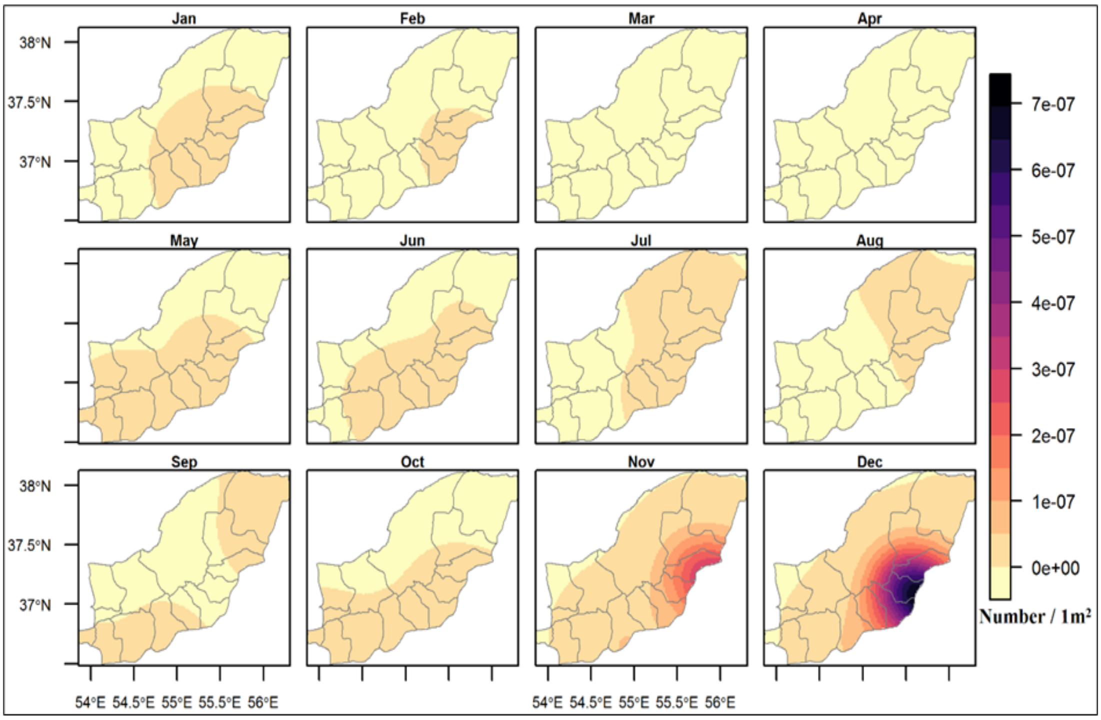

Figure 5. Spatial distribution of wildfire density in forest lands on monthly time scale in the statistical period of 2001-2021

3.2 Monitoring wildfire on annual time scale

In Table (1) and Figure 6, the output results of Moran's spatial autocorrelation analysis are presented to investigate and identify the spatial pattern of wildfires in the statistical period of 2001-2021. The results of spatial autocorrelation analysis for wildfire points, positive Moran values, and positive z-score values greater than 1.96 showed a spatial cluster pattern in the fires that occurred in Golestan in the period 2001-2021 statistics confirm.

Table 1. The results of Moran's statistics for wildfires in Golestan in the statistical period of 2001-2021.

Moran’s Index	Expected Index	Variance	Z-Score	P-value
0.41618	-0.07692	0.02473	2.392664	0.016727

Also, the spatial distribution of the pattern governing wildfire points in Golestan in the statistical period of 2001-2021 using the local Moran index (LISA) is presented in Figure 6. It is ten. In this figure, High-High(HH) indicates the occurrence of a high wildfire in a certain number of points and its adjacent points; High-Low (HL) indicates the occurrence of a high wildfire in a certain number of points and the occurrence of a low wildfire in its adjacent points, Low-High (LH) indicates the occurrence of a low wildfire in a certain number of points and high wildfire in the points around it, and Low-Low (LL) indicates low wildfire in a certain number of points and adjacent points. The local Moran index for the wildfires that occurred in Golestan showed two clusters, HH and LH; High values or positive spatial autocorrelation of HH were observed in the northern and northeastern parts, including Kalaleh and Gonbadkavus. The pattern of LH wildfire values was observed near the high-high cluster (HH) in the eastern part of Golestan.

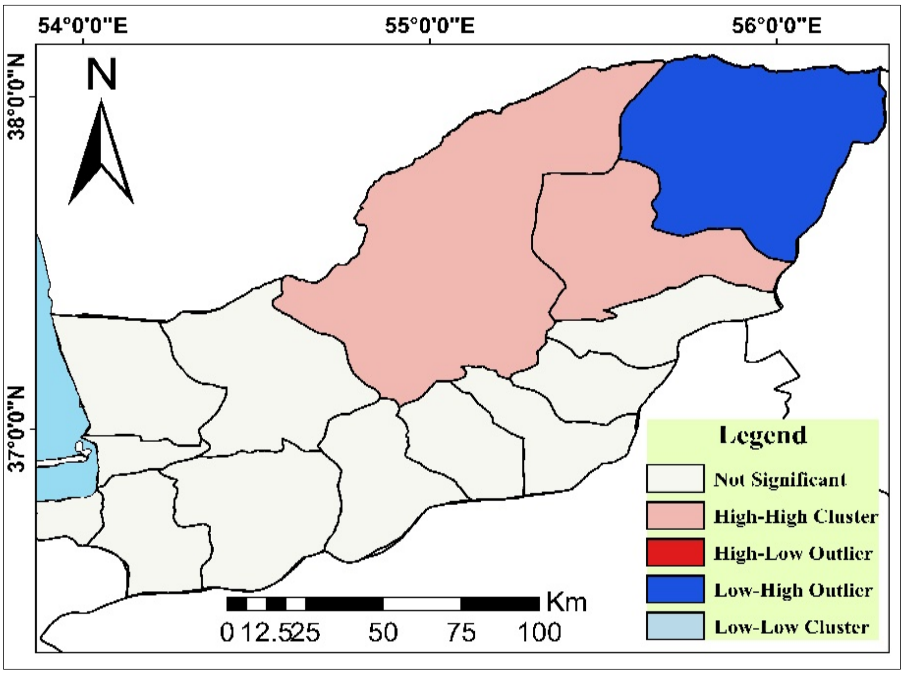

Figure 6. The distribution results of the local Moran pattern of wildfires in Golestan in the statistical period of 2001-2021

The wildfire density map shows the local Moran index (LISA) results. According to Figure 7, during the statistical period of 2001-2021, the extent and intensity of wildfire were more in the plains and foothills to the south and southeast of Golestan. The lowest extent and intensity of the wildfire corresponded to the eastern parts of the province. The easternmost part of Golestan has an average of 25,014 hectares without vegetation (Fig. 7).

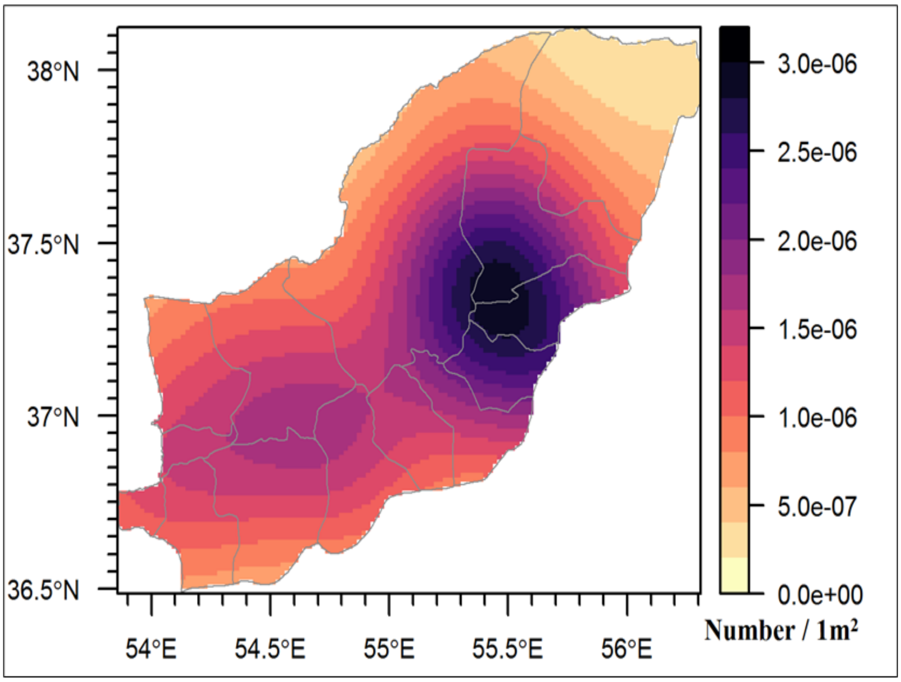

Figure 7. Spatial distribution of wildfire density in Golestan in the entire statistical period of 2001-2021

Figure 8 shows the annual spatial distribution of wildfire density based on the burned surface product data of the MODIS sensor for Golestan. During the study period (2001-2021), there were 18462 active fires in Golestan. The highest number of wildfires occurred in 2010, with 2517 wildfires (13.98%), followed by 2003 with 2163 wildfires (11.9%), and 2004 with 1982 wildfires (10.8%) had the highest number of wildfires. The lowest number of wildfires, with only 57 events (0.5%), was in 2001, followed by 2020 with 96 wildfires. The analysis of the annual spatial distribution of wildfires based on the data of the burned area product of the MODIS sensor showed that the spatial pattern of the occurrence of wildfires in the statistical period of 2001-2021 was not homogeneous (Fig. 8). The highest number of wildfires occurred in forest lands, with 900 incidents in 2010, mainly in the southern and southeastern parts, including Azadshahr, Ramian, Aliabad, Galikesh, Gorgan, and Minodasht. According to Figure 8, from 2011 to 2021, the extent and intensity of the wildfire was much less than in 2010, and only in 2015 in some parts of Gorgan (11 incidents), 2016 in the southeast, including Kalaleh, Minodasht, Galikesh, and Maraveh-Tepe (43 incidents); 2017 in the south, including the cities of Ramyan and Galikesh (86 incidents), 2019 in Azadshahr (19 incidents) and 2021 in the southern region. In Azadshahr, Aliabad, Kordkoi, and Galiksh (34 incidents), wildfires were observed in forest lands (Deciduous needleleaf trees and deciduous broadleaf trees). The lowest extent and intensity of wildfires in pasture lands were related to 2011 and 2015. In the years mentioned, wildfires in agricultural lands were far more than in other natural areas. The largest extent and number of wildfires in pasture lands were related to 2003 and 2009, with the number of 567 and 468 incidents, respectively, which mainly corresponded to the pasture lands of Kalaleh, Gonbadkavus and Marawah Tepe. Also, in 2004, 2005, 2006, 2007, 2008, 2009, 2012, 2013, 2014, 2016, 2018, 2019 and 2021, there were more pasture lands than forest lands, which mainly dominated the pasture lands in the north and northeast regions (Marawah-Tepe, Kalaleh, Gonbadkavus and Agh Qala). According to Figure 8, in most of the studied statistical period (2001-2021), the extent and intensity of wildfires in agricultural lands (Mostly in wheat and barley fields) were more than in other natural areas. Many changes were observed in the trend and extent of wildfires in agricultural lands; however, the highest number of wildfires in agricultural lands were related to 2003 (1665 incidents), 2004 (1635 incidents), and 2010 (1427 incidents) and 2015 (1119 incidents) respectively. In this regard, the investigations indicate that in 2010 there were the most favorable climatic conditions for wildfire occurrence (Eskandari, 2015).

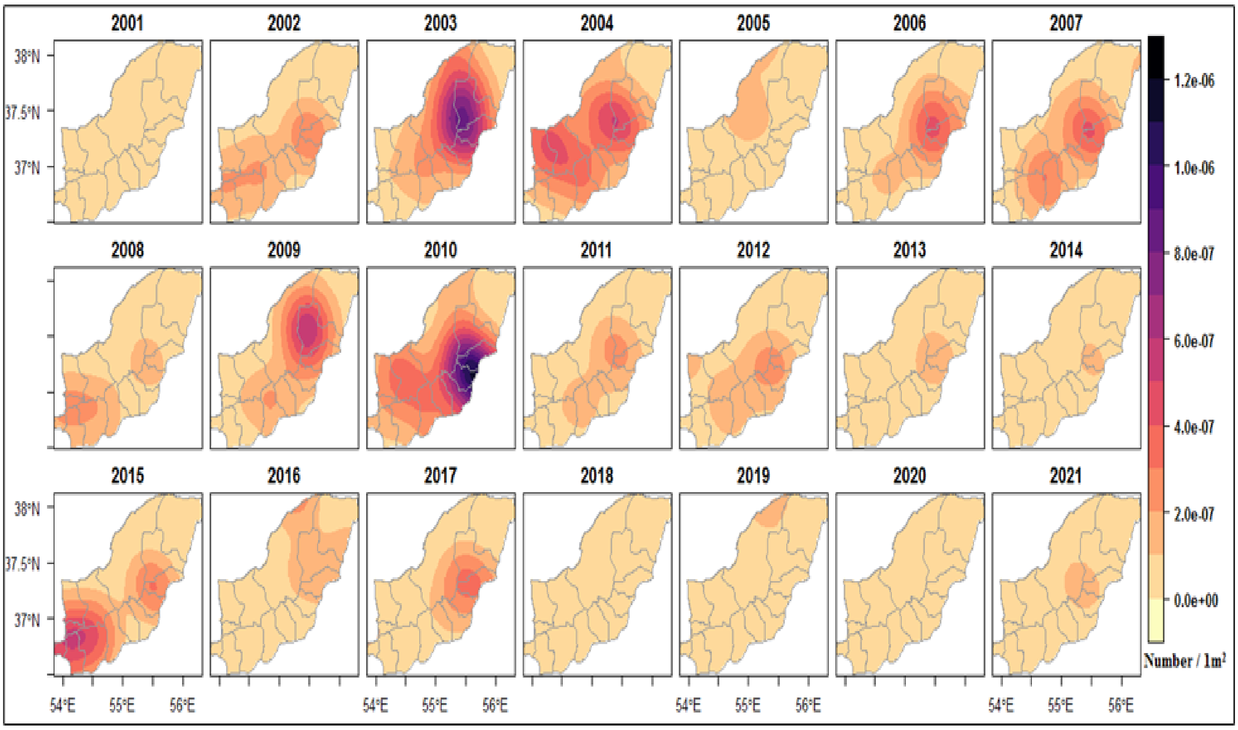

Figure 8. Spatial distribution of wildfire density on annual time scale in the statistical period of 2001-2021

The results of Kendall's trend test based on the data of the MCD64A1 product in the statistical period of 2001-2021 indicated that the occurrence of wildfire in Golestan in parts of the north-eastern and north-western regions at the probability level of 0.1% And between the foothills and the Gorgan River in the central areas, parts of the Galikash and Minodasht forest lands in the south-east and south have a significant increasing trend at the probability level of 0.05%. No statistically significant trends were observed for other regions (Fig. 9).

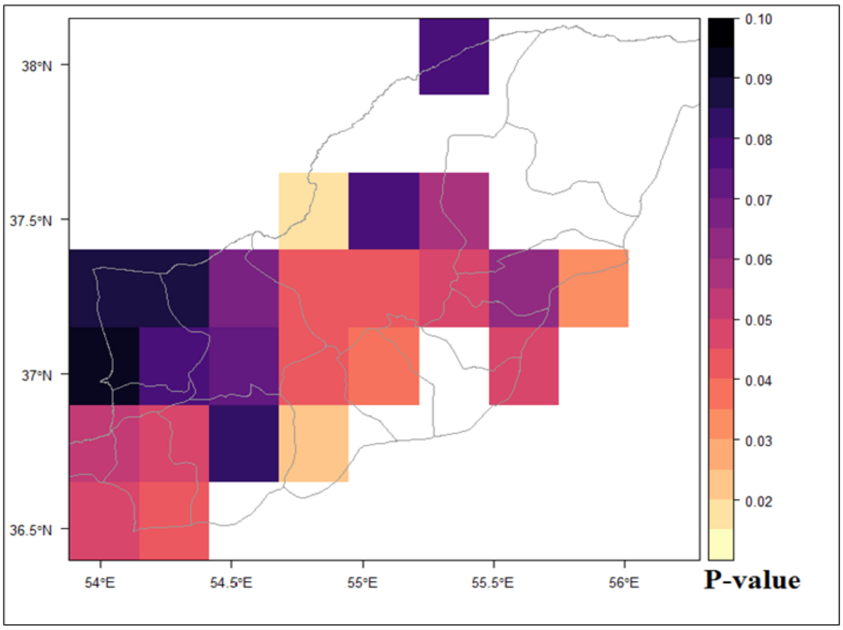

Figure 9. The trend of the burnt surface changes based on the data of the MCD64A1 product in the statistical period of 2001-2021

3.3 Monitoring of wildfire events in different physiographic units of the earth

3.3.1 Height

Figures 10 and 11 show the frequency of wildfire occurrence and spatial distribution in pasture, agricultural and forest lands in different altitude classes. The results showed that, on average, 90 percent of the wildfires from 2001-2021 occurred in altitude zones of 0 to 500 meters, corresponding to the distance between the foothills and the Gorgan River to the northern and northeastern parts are in Gonbadkavus, Aqqla, and Gamishan. This area covers 50% of the province and is wholly cultivated with crops (Mostly wheat and barley crops). Also, in some of its foothills, gardening is carried out.

The highest frequency of wildfires in pasture and agricultural lands was related to this altitude class (0-500 meters). According to Figures 10 and 11, wildfires in forest lands (Mostly in Deciduous needleleaf trees and deciduous broadleaf trees) have gradually increased towards higher altitudes (500-1000 and 1000-1500 meters). The highest wildfire frequency in forest lands was observed in the altitude class of 500-1000 meters (28%), followed by the altitude class of 1000-1500 meters (26.7%). According to Figures 10 and 11, the more we move towards higher altitudes in the southern parts of the province, the frequency of wildfire points decreases.

Figure 10. The frequency of wildfires in pasture, agricultural and forest lands in different altitude classes

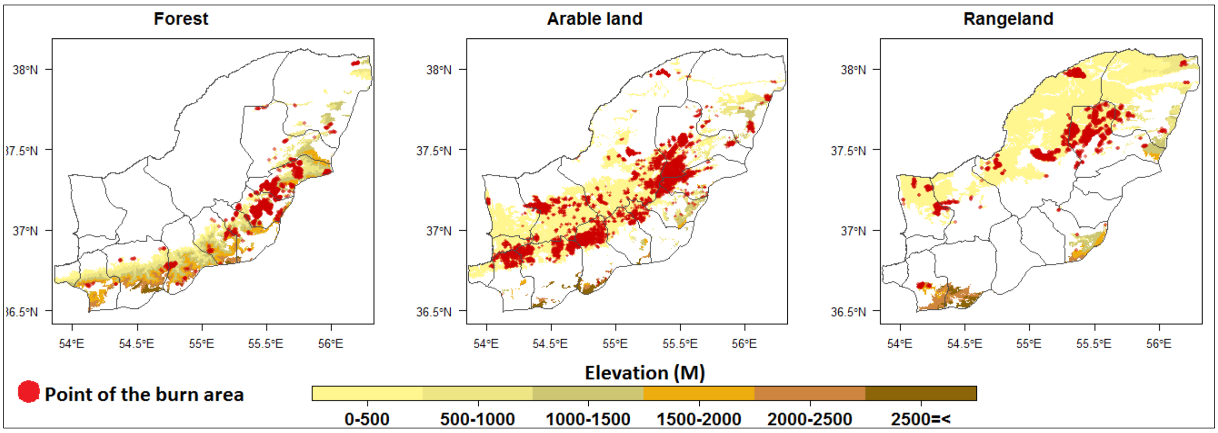

Figure 11. Distribution of wildfire points in different height classes

3.3.2 Slope

Figures 12 and 13 show the frequency of wildfire occurrence and spatial distribution in different slope classes in pasture, agricultural, and forest lands. According to Figure 13, a significant part of the area of Golestan, on average, 1,622,156 hectares, is located in the slope range of 0-15 degrees (80%). The highest number of wildfires were related to the 0-15- and 15-25-degree slope classes compared to other slope classes. The highest frequency of wildfire occurrences in agricultural and pasture fields of Golestan was related to the slope class of 0-15 degrees (more than 90%). This slope is mainly suitable for agricultural uses. Also, the results showed that with the increase of the slope classes, the frequency of wildfire occurrences decreases, so the number of wildfire occurrences in the slope class of 45-55 degrees was, on average, 0.6%, corresponding to the southern district's forest lands (Deciduous needleleaf trees, deciduous broadleaf trees and evergreen broadleaf trees). The south of the province is from Galiksh to Kordkoi. Examining the frequency of wildfire occurrences in agricultural, pasture, and forest lands showed that with the increase of slope classes, the frequency of wildfire occurrences in forest lands increases compared to agricultural and pasture lands. The highest frequency of wildfire occurrences in forest lands was related to the slope class of 15-25 degrees and then the slope class of 25-35 degrees, in such a way that, on average, 44 and 25.1 percent of wildfires, respectively. Forest lands have occurred in these slope classes. Easy access to forest lands on this slope increases the risk of wildfire. The slope is directly related to the speed of wildfire spread. Steeper slopes are more exposed to the risk of wildfire because the progress of flames occurs quickly in steeper slopes. In other words, a high slope does not increase the wildfire potential. Instead, if a wildfire occurs in an area, the direction of its spread will be towards steep slopes, and the amount of destruction and damage will be higher in more severe slopes.

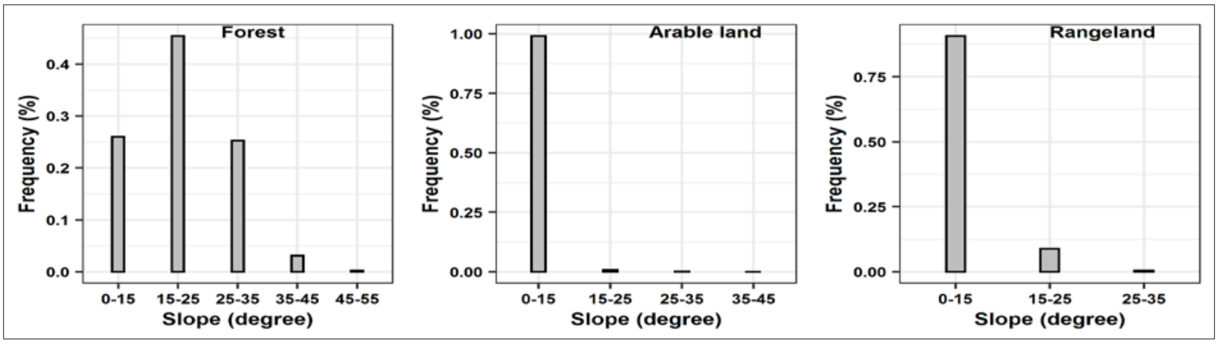

Figure 12. The frequency of wildfires in pasture, agricultural and forest lands in different classes of the slope

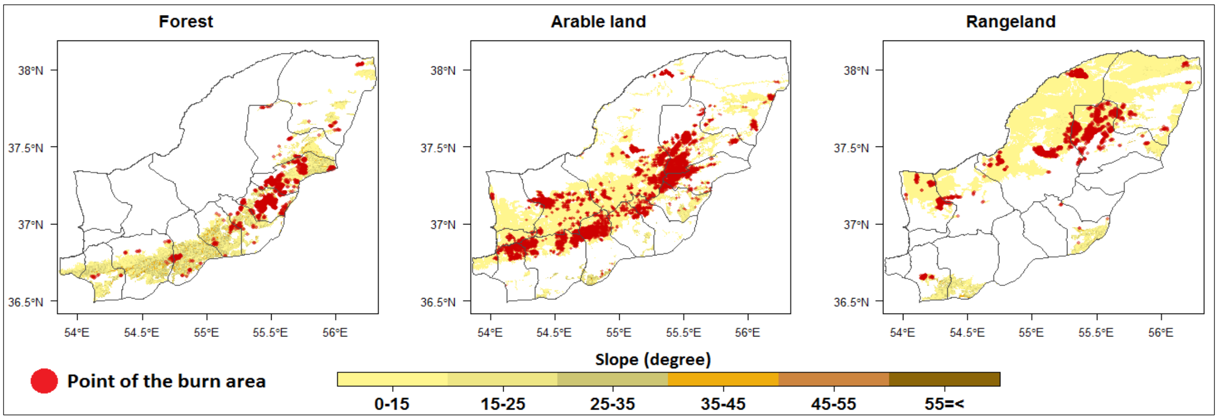

Figure 13. Distribution of wildfire points in different layers of the slope

4. Discussion

Golestan province has diverse vegetation, such as dense forests, grasslands, and steppes, and the risk of wildfire is a threatening factor for its forest ecosystems fire occurrence. So, in this research, the temporal-spatial pattern of wildfire was investigated using MODIS data, burnt area product (MCD64A1) in Golestan province located in the north of Iran for the statistical period of 2001-2021.

The results of this research indicated that the occurrence of wildfires in Golestan, especially in the northeastern regions, between the foothills and Gorgan River in the northwest, parts of the lands Galikash and Minodasht forests (Deciduous needleleaf trees, deciduous broadleaf trees, and evergreen broadleaf trees) in the south-east and south have had a significant increasing trend in the statistical period of 2001-2021. The plains and foothills in the northern and northeastern regions comprise wet and dry lands and good pastures. Gradually, as we move towards the northern part of the border of Turkmenistan, the vegetation of the province's pastures becomes more of a semi-desert steppe type. Dry and salt-loving plants can also be observed in the northern regions, in salt marshes. Mediterranean climate prevails in these regions and has relatively hot and dry summers. Also, due to the distance from the sea and the decrease in the altitude of the eastern Alborz, the rainfall is between 200 and 400 mm, which gradually decreases towards the north and reaches 100 to 150 mm. The totality of these conditions greatly increases the wildfire risk in these areas, and the slightest carelessness will cause a wildfire. Also, measures such as changing land use to agriculture play a significant role in increasing the occurrence of wildfires in these areas. Eskandari (2015), and Rahimi and Khademi (2018) also showed in their research that the number and extent of wildfires in the forests and pastures of Golestan has increased. Azizi et al. (2022) also concluded that the number of wildfires in the forests and pastures of Kermanshah province has increased. The review of various studies indicates that the increase in the number and intensity of wildfires is due to global warming and changes in land use. Eskandari and Jalilvand (2017) showed that the decrease in relative humidity is the most important climatic factor for the occurrence of widespread wildfires in Golestan forests. This was also confirmed by Banj Shafiei et al. (2014), Emami and Shahriyari (2020), Aleemahmoodi Sarab et al. (2013), Fan et al. (2023), Villar-Hernández et al. (2022), and Antonio and Ellis (2015). They said that in the conditions of increasing temperature, decreasing precipitation, and relative humidity, suitable environmental conditions are available for the occurrence and spread of wildfire. Some studies also indicate that the human factor plays a major role in the occurrence of wildfires and will intensify if the climatic conditions are suitable (Mirdeilami et al., 2014; Faramarzi et al., 2014). During the study period (2001-2021), there were 18,462 active fires in Golestan. The annual fire distribution density based on the wildfire data of the burned area product of the MODIS sensor showed that in the statistical period of 2001-2021, the highest number of wildfires was related to the year 2010 with 2562 wildfire cases (13.8%) and after it was the subject of wildfire in 2003 with 2022. Ghazanfar Pour et al. (2017), Eskandari (2015), Eskandari & Jalilvand (2017) and

Abdi et al. (2018) also showed that the most significant number and extent of wildfires in the natural areas of Golestan in the years that mentioned has happened. Also, Azizi et al. (2020) showed that the frequency of wildfire in forest and pasture areas of Kermanshah province in 2010 was more than in other years. It seems that in addition to human factors, climatic factors were also influential in the occurrence of wildfires in 2010. In this regard, Eskandari (2015) and Eskandari & Jalilvand (2017) concluded their research that in 2010 the most favorable climatic conditions (dry air, decrease in relative humidity, drying of dead leaves, increase in average annual temperature, and blowing hot winds) for the occurrence of wildfire. Generally, Golestan is one of the critical centers of agriculture in the country and carrying out measures such as the wildfire in order to clear the fields and also change the use to agriculture, including the reasons for the occurrence of fire in the area of agricultural use between the foothills and Gorgan is a river. However, in addition to human factors, climatic factors include dry air, low amount of moisture in dead leaves (Mostly in wheat and barley fields) and their dryness, decrease in relative humidity, increase in average annual temperature, and blowing hot winds provide favorable conditions for the progress of these wildfires. Also, the time series analysis of wildfire occurrences based on MODIS wildfire sensor data showed that wildfire occurrences in Golestan have a seasonal pattern. The results indicated that 75% of the wildfires occurred in the hot period (spring and summer), and the other 24.7% occurred in the cold period (autumn and winter).

The largest spatial extent of the occurrence of wildfires in agricultural lands (Mostly in wheat and barley fields) was related to May, June, July, and August, corresponding to the cultivation areas between the foothills and the Gorgan River. In Golestan, the rainfall decreases from the end of spring. In this way, the decrease in precipitation and the increase in temperature causes the plant mass to lose its moisture and provide suitable conditions for the surface wildfire of litter in the hot period of the year. Also, carrying out measures such as cleaning the fields to eliminate agricultural waste provides the basis for the occurrence of wildfire. Also, most wildfires occur in pasture lands from mid-summer to early autumn, which covers a significant part of pasture lands in the northeastern and northern regions of the province. The results indicated that wildfires in the forests of Golestan are more frequent in the cold seasons (autumn and winter) than in other regions of Iran. Rahimi and Khademi (2018), Farajzadeh et al. (2015), and Azizi and Yousofi (2009) also concluded that the majority of wildfires in the forests of northern Iran are related to the cold period of the year. The increase in temperature and the loss of soil moisture in winter increase the probability of wildfire disasters in winter (Fan et al., 2023). Foehn Wind plays a significant role in wildfires in the forests and pastures of Golestan during the year's cold period. Golestan province, due to its location on the northern slopes of Alborz, the existence of northern currents in the region during different seasons of the year has favorable conditions for creating warm winds. Foehn Wind, which flows from the south side of the Alborz mountains to the plains of the Caspian Sea in autumn and winter, is a hot and dry wind that raises the environment's temperature by several degrees and causes wildfires. These winds blow every year 5-6 times in winter and once or twice in spring. The maximum duration of warm winds is 2 to 3 days, and their speed is 20 to 25 meters per second, increasing the air temperature by 10 to 19 degrees (Rahimi & Khademi, 2018; Azizi & Yousofi, 2009). Various studies in Iran and the world have proven the effect of climate on the occurrence of wildfires (Bahadur Bhujel et al., 2022; Salsabila et al., 2020; Azizi & Yousofi, 2009). In this regard, based on the research results of Bolaño-Diaz et al. (2022), it was found that 87% of the wildfires in Colombia occur during the dry season (December to March). At the same time, the results of some other studies indicate that due to the increase in temperature and a significant decrease in precipitation and soil moisture, most wildfires occur in the hot period of the year (Azizi et al. 2022; Zheng Z. et al., 2021; Bahadur Bhujel et al., 2022). In addition to climatic conditions, the physical characteristics of the land are also effective in wildfires. The results showed that, on average, 90 percent of the wildfires from 2001-2021 occurred in altitude zones of 0 to 500 meters, corresponding to the distance between the foothills and the Gorgan River to the northern and northeastern parts are in Gonbadkavus, Aqqla, and Gamishan. In this altitude class, intentional and unintentional human errors such as change of use, setting wildfire to straw and stubble, and flaming towards pastures play a significant role in wildfire occurrence. Also, in this altitude layer towards the northern parts, the amount of precipitation and relative humidity is lower, and the temperature is higher, which increases the probability of wildfire occurrence. In this regard, Rahimi & Khademi (2018) also showed that 0-254 meters high has the highest frequency of wildfires in Golestan because there is a possibility of a sudden increase in temperature in this high-altitude class. In Gilan province located in the north of Iran, the highest frequency of wildfires occurs at heights less than 150 meters (Farahi et al., 2012). The results indicated that the wildfire in the forest lands gradually increases towards the higher altitude classes (500-1000 and 1000-1500 meters). According to the results of Janbazghobadi (2019), most of the wildfires in the province occurred at an altitude of 700 to 1500 meters, which is consistent with the results of the present study. The highest wildfire risk in Golestan National Park is related to the height classes of 500-1000 and 1000-1500 meters (Mirdeilami et al., 2014). Normally, the wildfire risk should be reduced with increasing height. However, sometimes the prevailing ecological conditions cause the density of vegetation to increase so much that it leads to the density of flammable materials. As a result, the effect of reducing relative humidity is minimized (Dashti et al., 2021). On the other hand, the location of residential areas and the concentration of population and the proximity of agricultural lands and the spread of intentional wildfires created in agricultural lands in these altitude classes, and the easy access of tourists and hunters to these altitude classes are among other reasons for wildfires in these altitude classes (Gholamrezaei et al., 2022; Mirdeilami et al., 2014). In higher altitude classes, precipitation and relative humidity are high, and the average temperature is low. Also, the amount of vegetation and combustible material at higher altitudes is less, and it is more difficult for tourists to access these areas, which all these conditions reduce the probability of wildfire in these areas.

The slope of the land is one of the influencing factors in the speed and direction of wildfire propagation. This research indicated that the highest number of wildfires in Golestan is related to the slope range. It is 0-15 degrees (80%), which is consistent with the research results of JanbazGhobadi (2019), Jafari et al. (2015), and Rahimi & Khademi (2018) in Golestan, and Hedayati et al. (2019) in Kurdistan province. Also, the highest frequency of wildfire occurrences in forest lands was related to the 15–25-degree slope layer and then the 25-35 degrees slope layer, so on average, 44 and 25.1 percent of wildfires in forest lands have occurred in these slope classes. Gholamrezaei et al. (2022), in their research on the occurrence of wildfire in the forests of Kermanshah province, concluded that the highest rate of forest wildfire occurs in the 15-30% slope class and the reason for this it can be said that the presence of wooded pastures in this slope layer creates a suitable perspective for attracting more tourists and as a result increases the risk of wildfire starting and spreading. Wildfire propagation and spread speed on high slopes are much higher than on low slopes (Banales-Seguel et al., 2018). In high slopes, usually due to the general tendency of trees and the availability of the branches of the tree's lower trunk, the surface wildfire turns into a crown and trunk wildfire. It causes a change in the type of wildfire and its intensification (Nasiri et al., 2012).

5. Conclusion

Investigating forest wildfire occurrence's spatial and temporal patterns is crucial for forest fire management decision-making. Therefore, in this research, the spatial and temporal patterns of wildfire occurrence in agricultural, pasture, and forest lands of Golestan in the statistical period of 2001-2021 were investigated using the fire products of the MODIS sensor. The frequency of wildfires was higher in the hot period of the year (spring and summer). However, the period of occurrence of wildfire and the peak of wildfire changes in different uses. The frequency and spatial extent of wildfires in agricultural lands in May to July, in the pasture lands in July, August, and September, and in forest lands in November and December were more than in other months.

Also, the results indicated that the extent and intensity of the wildfire were more significant in the plains and foothills to the south and southeast of Golestan. The lowest extent and intensity of the wildfire corresponded to the eastern parts of the province.

The risk of wildfire depends largely on weather variables and fuel conditions. Considering the spatial distribution and temporal pattern of wildfires, especially wildfires in forest lands during November and December which coincide with Foehn Wind hot weather in the northern regions, it can be said that weather conditions play an important role in the occurrence of wildfires in Golestan. A significant part of the forests of in this province consists of deciduous broad-leaved trees. In autumn, many leaves fall, and many dead leaves accumulate on the ground; In such a situation, the occurrence of hot wind, temperature increase, and decrease in soil moisture increase the risk of wildfire. Therefore, due to global warming and the significant role of meteorological variables in wildfire, wildfire behavior assessment and prediction are influential in reducing and preventing damage. It also provides the possibility of proper management in this area.

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