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Effects of natural and anthropogenic factors and their interactions on dust events in Northern China

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ABSTRACT

Aeolian dust can influence the climate, air quality, human health, and ecosystems. Dust events in Northern China are the main contributors to dust aerosols in the world, but the impacts of meteorological and anthropogenic factors and their interactions on dust events remain unclear. This study analyzed the spatial and temporal variations of dust event frequencies and quantitatively investigated the impacts of meteorological conditions, anthropogenic factors, and their interactions on dust events using the geographical detector model (GeoDetector) in Northern China. Results revealed that the dust event frequency significantly decreased by 0.006 times yr^{-1} per site during 1980–2007. At the regional scale, there were large seasonal variations in the effects of meteorological conditions and anthropogenic factors on dust events. Strong winds and soil surface conditions are main drivers of dust events in spring. In summer and autumn, anthropogenic factors have significant impacts on the occurrence of dust events, but the frozen period and relative humidity are major impacting factors in winter. Effects of natural and anthropogenic factors on dust events showed great spatial and seasonal disparities over different vegetation regions. Interactions between two factors enhanced their impacts on the occurrence of dust events. There are also large spatial and seasonal variations in the primary interactions on dust events over different vegetation regions. The findings could help us to better understand the relative importance of various factors on dust events, which has important implications for improving the prediction of dust emission models and developing desertification control strategies.

1. Introduction

Aeolian dust from wind erosion is the most abundant type of aerosol in the atmosphere (Kok et al., 2018); it mainly originates from arid and semi-arid areas in the world (Wang et al., 2015, 2017; Song et al., 2016). Dust aerosols can be transported over thousands of kilometers. They influence the global climate by scattering and absorbing radiation, serving as a nuclei for cloud formation, and fertilizing ecosystems through dust deposition (DeMott et al., 2010; Yan et al., 2011; Yang et al., 2016; Kok et al., 2018; Song et al., 2019). They can also affect air quality (Wang et al., 2018a; Li et al., 2019) and human health (Lelieveld et al., 2015) by increasing the particulate matter concentrations.

Dust events generally occur when the surface wind velocity exceeds a certain threshold friction velocity (Song et al., 2017). This threshold is determined by a combination of natural (e.g. wind velocity, precipitation, soil moisture, soil properties, vegetation growth) and anthropogenic (e.g. land use, agriculture, livestock, mowing) conditions. However, it remains unclear what roles these driving factors and their interactions actually play in the occurrence of dust events. Understanding these roles could help us improve the prediction capability of dust emission models.

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Numerous studies have been conducted to explore the impacts of various potential driving factors on dust events. Changes in the surface conditions of source areas and variations in the wind velocity in the near-surface layer are generally recognized as the two main reasons for the variations in the frequency and distribution of dust events (Yu et al., 2009; Shen et al., 2018). Both of these reasons are closely related to the global climate change (An et al., 2018). In addition, precipitation, soil moisture, air temperature, surface soil conditions as well as human activities play important roles in the determination of the vegetation growth and thereby influence dust events (Kimura et al., 2009; Lee and Sohn, 2011; Wang et al., 2018b).

Relationships between dust events and conditions of the climate and ground surface have been analyzed in previous studies. Wind speed has been recognized as a predominant driving factor in dust processes (Rashki et al., 2018; Shen et al., 2018). Numerous studies have suggested that the frequency of dust events increased with increasing wind speeds (Wu et al., 2018; Wang et al., 2019). Dust events always negatively correlated with precipitation by the improvement in soil moisture or vegetation growth (Kang et al., 2016; Namdari et al., 2018). The mechanisms of effects of temperature on dust events are complex, as positive and negative correlations exist simultaneously (Song et al., 2016, 2017; Singh et al., 2017). Several studies have indicated that changes in relative humidity contribute to most of the variability in surface soil moisture, which, in turn, has significant influences on the threshold friction velocity (Ravi et al., 2004; Ju et al., 2018). Moreover, some studies have explored the influence of land use (Li et al., 2014; Xi and Sokolik, 2016; Du et al., 2017; Galloza et al., 2018), gross domestic product (GDP) (Jiang et al., 2016), and population (Guan et al., 2016) on the occurrence of dust events.

Although previous studies have identified correlations between dust events and the natural and anthropogenic conditions using traditional methods such as linear/nonlinear regression based on datasets of monitoring (Kang et al., 2016), remote sensing (Namdari et al., 2018), model simulations (Song et al., 2017), wind tunnel experiments (Ravi et al., 2004), and field experiments (Ju et al., 2018; Wang et al., 2019). However, these investigators usually focused on unilateral effects of natural or anthropogenic factors through identifying the correlations between dust events/emissions and impacting factors. The relative importance of these factors in the occurrence of dust events have been rarely quantified. In addition, they also did not consider the potential for interactive effects between factors impacting dust events, but these methods have limited capabilities in examining the interactive effects of driving factors on dust events.

The arid and semi-arid region in Northern China is a main contributor to global dust emissions (Song et al., 2019). Quantifying influences of potential factors and their interactions are essential for understanding the relative importance of potential driving factors in dust emissions. In this study, the geographical detector model (GeoDetector) was adopted to quantitatively investigate the importance of natural conditions (e.g., air temperature, precipitation, relative humidity, air pressure, surface frozen period, vegetation, etc.) and anthropogenic factors (e.g., land use, cultivated land, population, and GDP) and their interactions on the occurrence of dust events.

2. Materials and methods

2.1. Study area and influencing factors

The study area is the arid and semi-arid regions in Northern China with temperate continental climate (Fig. 1). The total area accounts for approximately 30% of the China territory with mean annual precipitation less than 400 mm and the annual mean temperature ranging from 0 °C to 13 °C (Song et al., 2019).

To investigate the relative importance of driving factors in the occurrence of dust events in Northern China, we selected 15 natural and four anthropogenic factors (Table 1) according to previous studies (Guan et al., 2016; Jiang et al., 2016; Song et al., 2016; Du et al., 2017; Ju et al., 2018). Among these factors, the frozen period (FP) of each site refers to the largest number of days between freezing and thawing dates throughout the whole year. The dates of the surface temperature below or above 0 °C for five consecutive days were used to determine the surface freezing and thawing dates, respectively.

2.2. Datasets

The daily dust event records and daily average meteorological data at 152 stations (Fig. 1) were obtained from the China Meteorological Data Service Center during the period of Jan. 1, 1980-Dec. 31, 2007. Dust event data are calculated based on the records of basic land-based stations in China. These stations cover most of vegetation types in the research region. The land use data for 1980s, 1995, and 2000 were obtained from the Data Sharing Infrastructure of Earth System Science, which had a map scale of 1:100,000. Data in 1980s, 1995, and 2000 were considered as the land use data during 1980–1989, 1990–1999, and 2000–2007, respectively. The monthly Normalized Difference Vegetation Index (NDVI) datasets during 1982–2007 were obtained from the Global Inventory Modeling and Mapping Studies (Tucker et al., 2005) with a spatial resolution of 8 km × 8 km, which were used to calculate the vegetation cover by using the method of Gutman and Ignatov (Gutman and Ignatov, 1998). GDP, CUL, and POPU data were obtained from China's statistical yearbook. All the data used for the analyzing were the long-term monthly averages at 152 meteorological stations. For anthropogenic variables, the annual average throughout the whole year at each station was used as the monthly average and was extracted from maps of anthropogenic factors using ArcGIS 10.3 software (http://www.esri.com). The quality-control procedures were thoroughly applied and evaluated in datasets of daily meteorological data (Feng et al., 2004), land use (Liu et al., 2002; Ran et al., 2010), and NDVI (Tucker et al., 2005).

2.3. GeoDetector q statistic

In this study, GeoDetector q statistic was used for quantifying impacts of meteorological and anthropogenic factors and their interactive effects on dust events in Northern China. GeoDetector q statistic is a spatial variance analysis model that can be used to assess non-linear associations between potential factors and target geographic phenomena (Wang et al., 2010, 2016; Wang and Xu, 2017). The core underlying assumption of the model is that if an X (explanatory variable) causes Y (explained variable), then their spatial distribution would be consistent. Compared with commonly used linear models, GeoDetector q statistic is capable of taking advantage of categorical explanatory variables, detecting the dominant factor, and assessing the effect of interaction between two X variables on Y without the restriction of linearity assumption and immunity to the collinearity.

The spatial association between X (e.g. natural and anthropogenic factors in this study) and Y (e.g. dust events in this study) can be measured by the q statistic which is defined as follows:

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma_X^2} = 1 - \frac{SSW}{SST}$$
$$SSW = \sum_{h=1}^{L} N_h \sigma_h^2$$
$$SST = N\sigma_X^2 \quad (1)$$

where $h = 1, 2 \ldots L$ denotes the strata of factor X. N_h and N denote the number of samples in stratum h and the total number of samples over the whole study region, respectively. SSW and SST denote the sum of variance and global variance in stratum h and in the whole study area, respectively. The factor detector can be used to explore the extent to which factor X explains the spatial variation of variable Y. The interval of q is [0, 1], and the value means that a factor X explains $q \times 100\%$ of the dust events. The bigger the q value, the larger the non-linear

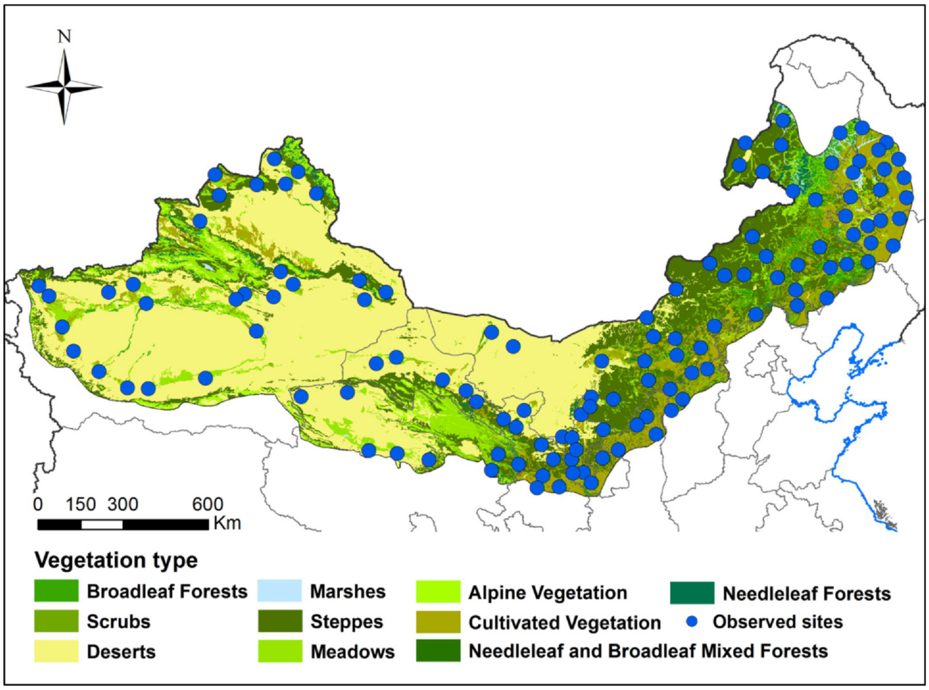

Fig. 1. Spatial distributions of vegetation types and meteorological stations (blue circles) in Northern China. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

association with regard to dust events. If spatial distribution of dust events is completely determined by a factor X, the q value is 1, and if dust events and a factor X have no spatial association with each other, the q value is 0.

The interactive effect of two X factors on dust events also can be quantified by q statistic. The index can be used to assess the interactive effects of two factors by comparing value of $q(X1 \cap X2)$ with values of $q(X1)$ and $q(X2)$. The interaction of two variables ($X1 \cap X2$) was calculated by overlaying the two variables layers in GIS tools. Furthermore, the interactive relationship can be interpreted in terms of five categories by comparing the interactive q value of the two factors and the q value of each of the two factors. These five categories are as follows:

$$\text{Nonlinear} - \text{weakened}: \; q(X_1 \cap X_2) < M\text{in}(q(X_1), q(X_2))$$

$$\text{Uni} - \text{enhanced} = \text{weakened} : \text{Min}(q(X_1), q(X_2)) < q(X_1 \cap X_2) < Max(q(X_1), q(X_2))$$

$$\text{Bi} - \text{enhanced}: \; q(X_1 \cap X_2) > Max(q(X_1), q(X_2))$$

$$\text{Independent}: q(X_1 \cap X_2) = q(X_1) + q(X_2)$$

$$\text{Nonlinear - enhanced}: q(X_1 \cap X_2) > q(X_1) + q(X_2)$$

The natural breakpoint stratification method was adopted to sort the original data because it can capture the smallest variance in stratum and largest variance between strata (Wang et al., 2010), which is consistent with the principle of GeoDetector q statistic.

3. Results

3.1. Spatial-temporal variations of dust events

Fig. 2 illustrates that severe dust events were mainly distributed in regions of desert and desertified lands, such as Southern Xinjiang, Gansu, and Western Inner Mongolia. The dust event frequency had large spatial differences in different vegetation types in Northern China. The annual mean dust event frequency was 0.42 times/site in Northern

Table 1
Natural and anthropogenic factors and their data sources.

Influencing factors		Data source
Natural factors	Relative humidity (RH) Precipitation: daily accumulated precipitation (PR), daily maximum precipitation (DMP) Daily air temperature at 2 m above the ground: mean highest temperature (MHT), highest temperature (HT), mean temperature (MT), lowest temperature (LT), mean lowest temperature, (MLT) Air pressure: mean air pressure (MP), highest air pressure (HP), lowest air pressure (LP) Daily wind speed at 10 m above the ground (MWS) Mean water pressure (MWP) Surface frozen period (FP)	China Meteorological Data Service Center: http://data.cma.cn
	Vegetation coverage (VC)	Calculated from NDVI data of Global Inventory Modeling and Mapping Studies
Anthropogenic factors	Land use (LU)	Data Sharing Infrastructure of Earth System Science: http://www.geodata.cn/
	Population density (POPU) Cultivated vegetation (CUL) GDP per unit area (GDP)	China's statistical yearbook: http://data.cnki.net/Yearbook

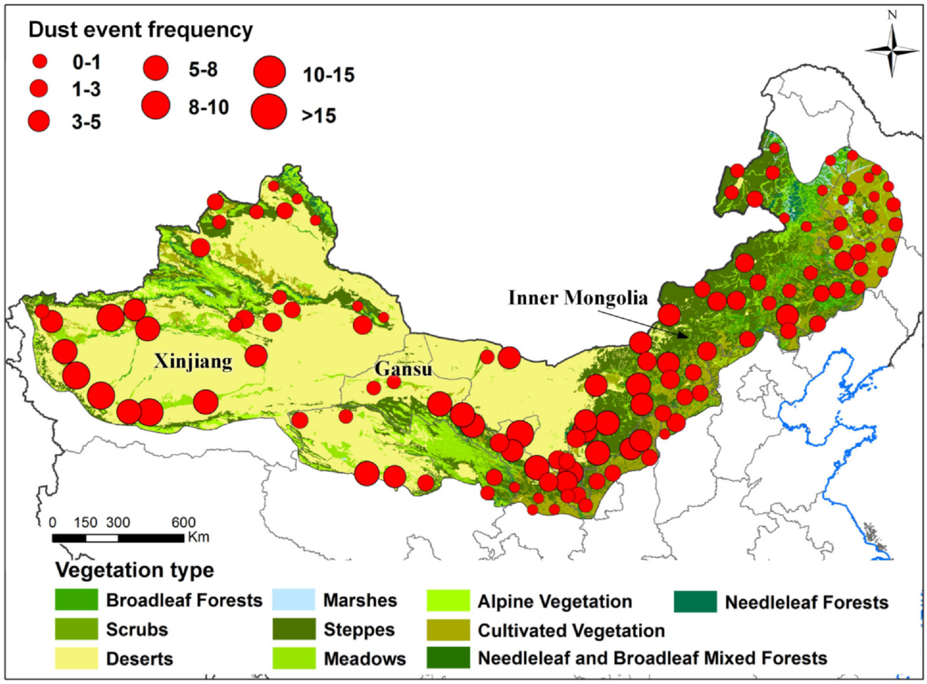

Fig. 2. Map of vegetation type and annual dust event frequency (red circles) in Northern China. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

China during 1980–2007. Areas with cultivated vegetation had the largest annual dust event frequency (3.14 times/site), followed by deserts (0.55 times/site), steppes (0.50 times/site), meadows (0.29 times/site), and broadleaf forests (0.09 times/site).

Fig. 3 shows that the frequency of dust events in Northern China has significantly declined from 1980 to 2007. The annual dust events declined approximately 0.006 times/site during this period. The most and least severe dust events occurred in 1982 (0.256 times/site) and 1997 (0.047 times/site), respectively. However, the dust event frequency showed an upward trend from 1997 to 2001, followed by a downward trend (Fig. 3a). Dust events mainly occurred in spring (2.866 times/site), followed by summer (1.234 times/site), winter (0.539 times/site), and autumn (0.320 times/site) (Fig. 3b).

3.2. *Impacts of influencing factors on dust events*

3.2.1. *Impacts of factors on dust events at regional scale*

The effect of each independent factor on dust events was determined by calculating its q value (Fig. 4), which indicated the relative importance of each factor in the occurrence of dust events. We found that land use and relative humidity were the two primary factors ($q > 0.15$) impacting dust events at the annual time scale, followed by precipitation, vegetation coverage, and air pressure.

There were large seasonal variations in the impacts of driving factors on dust events in Northern China (Fig. 4). Air pressure (LP, MP, and HP) and temperature (MT and MLT) were dominant drivers ($q = 0.30$) in spring, followed by RH ($q = 0.22$), VC ($q = 0.19$), MHT ($q = 0.15$), LU ($q = 0.14$), HT ($q = 0.11$), and FP ($q = 0.10$); GDP ($q = 0.04$) and POPU ($q = 0.03$) had the lowest impacts. In summer, the land use was the primary impacting factor ($q = 0.19$), while other factors had weak impacts ($q < 0.09$). In autumn, however, dominant factors were GDP ($q = 0.17$) and LU ($q = 0.14$), and in winter, FP ($q = 0.25$) had the largest impacts, followed by RH ($q = 0.20$), temperature (HT, $q = 0.20$; MT and LT, $q = 0.18$; MLT, $q = 0.16$), air pressure (LP, MP, and HP) ($q = 0.18$), GDP (q = 0.15), VC ($q = 0.14$), and LU (0.13).

3.2.2. *Impacts on dust events in different vegetation regions*

Fig. 5 shows that the annual and seasonal impacts of potential driving factors on dust events exhibited large differences for the three different vegetation types (deserts: DES, steppe: STE, and cultivated vegetation: CULV). Generally, POPU dominated ($q = 0.59$) dust events in desert regions (Fig. 5a) at the annual time scale, followed by air pressure (HP and MP). Precipitation and vegetation cover exhibited weak association with dust events in desert areas. However, primary

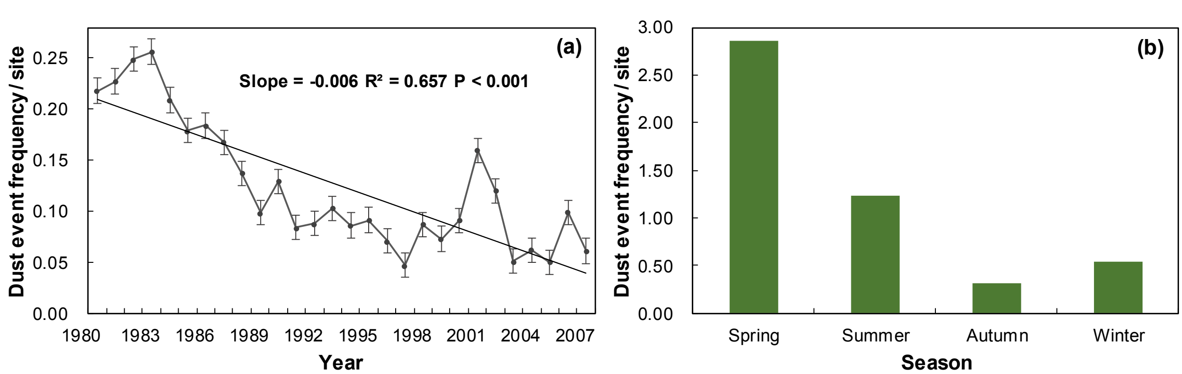

Fig. 3. Interannual (a) and seasonal (b) variations of the dust event frequency per site in Northern China.

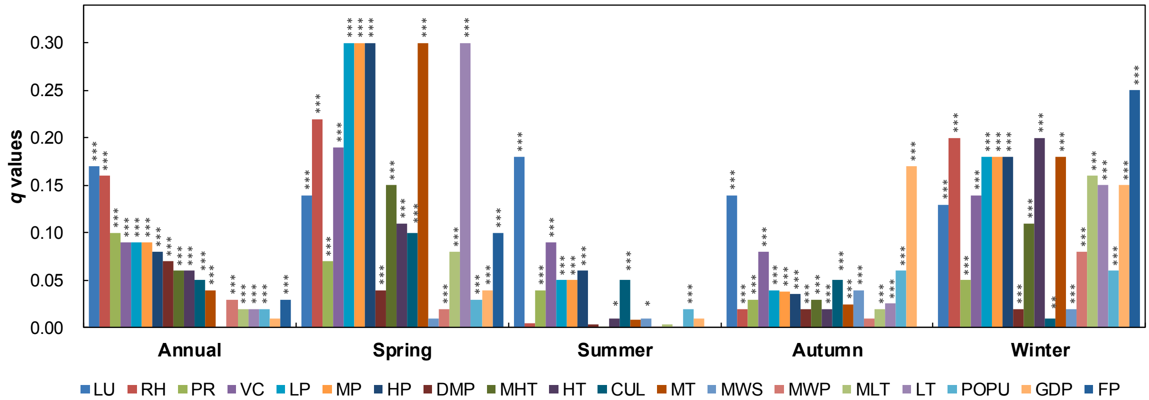

Fig. 4. Annual and seasonal q values of impacting factors for dust events at the regional scale. Note: ***, **, and * denote that q value is significant at levels of 0.001 ($p < 0.001$), 0.005 ($p < 0.005$), and 0.01 ($p < 0.01$), respectively.

impacting factors were LU (STE, $q = 0.26$; CULV, $q = 0.23$) and RH (STE, $q = 0.21$; CULV, $q = 0.17$) in both regions of steppe and cultivated vegetation (Fig. 5b and c).

In desert regions, the primary drivers were air pressures (LP, $q = 0.32$; MP, $q = 0.33$; and HP, $q = 0.34$) and land use ($q = 0.23$) in spring and summer (Fig. 5a), respectively. In autumn, GDP ($q = 0.17$) was the dominant factor, followed by LU ($q = 0.12$), POPU ($q = 0.11$), and VC ($q = 0.10$). In winter, however, the air pressures were the primary impacting factors

In steppe regions, LU ($q = 0.48$) and VC ($q = 0.39$) were dominant factors in spring, followed by air pressures (LP, $q = 0.27$; MP, $q = 0.22$; HP, $q = 0.23$), RH ($q = 0.22$), CUL ($q = 0.18$), and FP ($q = 0.13$) (Fig. 5b). LU ($q = 0.27$) was the primary controlling factor in summer, whereas the dominant controlling factor were GDP ($q = 0.50$) and LU

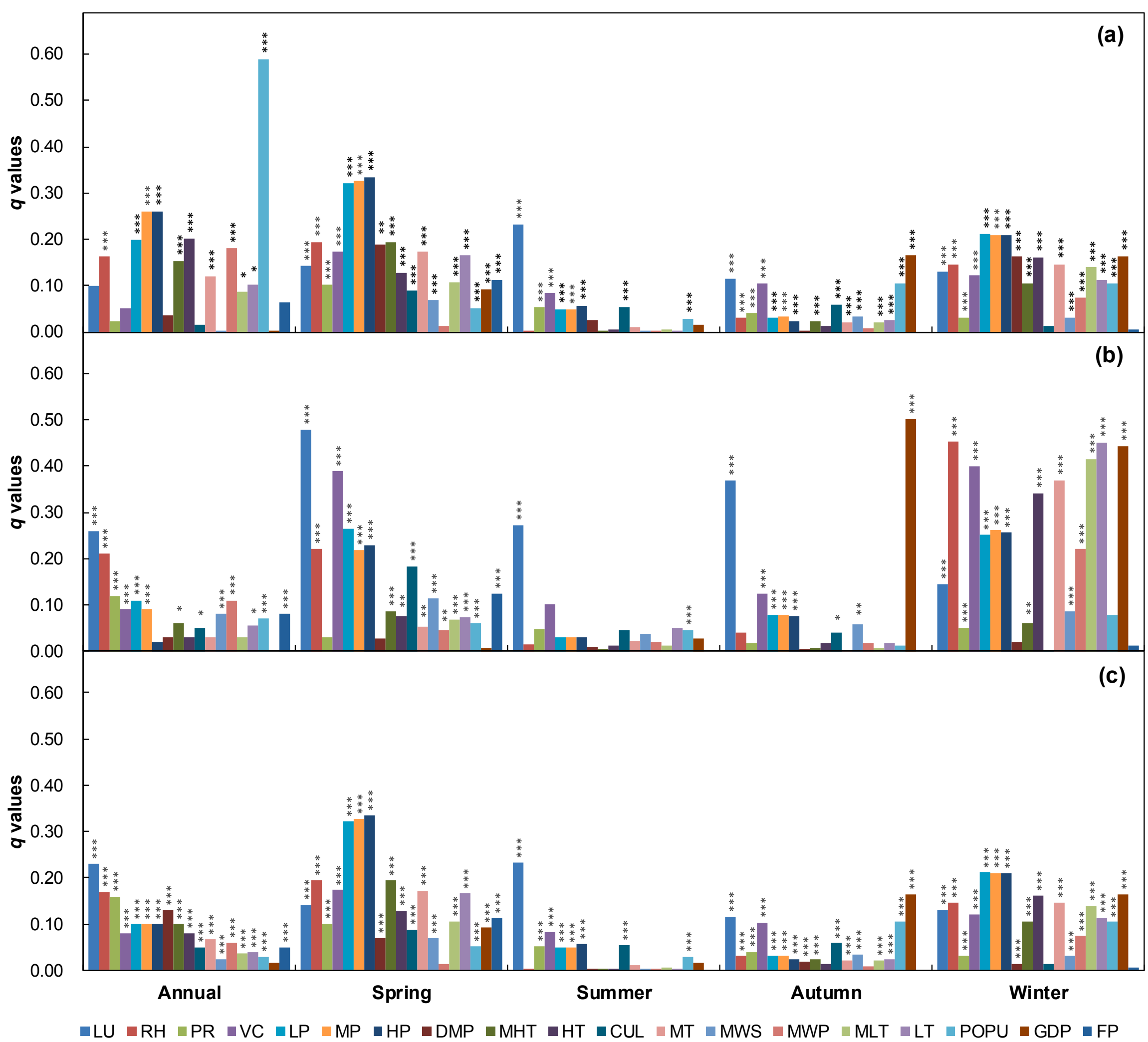

Fig. 5. Annual and seasonal q values of influencing factors in regions of deserts (a), steppe (b), and cultivated vegetation (c). Note: ***, **, and * denote that q value is significant at levels of 0.001 ($p < 0.001$), 0.005 ($p < 0.005$), and 0.01 ($p < 0.01$), respectively.

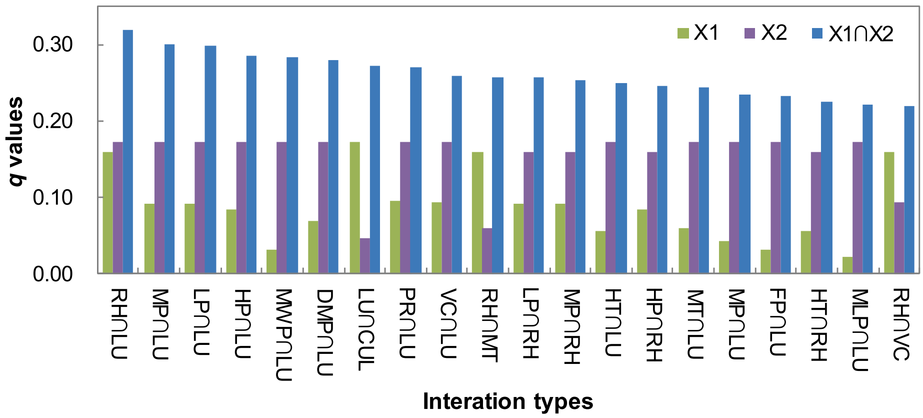

Fig. 6. Annual q values of interactions between potential impacting factors at the regional scale.

(q = 0.37) in autumn. In winter, however, factors such as RH (q = 0.45), LT (q = 0.45), and GDP (q = 0.44) were main impacting factors, followed by MLT (q = 0.42), VC (q = 0.40), MT (q = 0.37), and HT (q = 0.34) (Fig. 5b).

In cultivated regions, air pressures (LP, MP, and HP) ($q \approx 0.33$) played a dominant roles in dust events in spring, followed by RH (q = 0.20), MHT (q = 0.19), VC (q = 0.17), MT (q = 0.17), LT (q = 0.16), and LU (q = 0.14) (Fig. 5c). The primary factor was LU (q = 0.23) in summer, but GDP (q = 0.17), LU (q = 0.12), POPU (q = 0.11), and VC (q = 0.10) were main impacting factors in autumn. Similar to spring, the air pressure was also the dominant factor for the occurrence of dust events in winter.

3.3. Interactions of impacting factors

3.3.1. Interactive effects at the regional scale

Figs. 6 and 7 show the top 20 pairs of annual and seasonal interactions between the 19 factors examined in this study, respectively. The interactive q value of each pair of factors was larger than both q values of the two factors, and some of the interactive q values were larger than the sum of the two factors' q values. This indicated that the interactive relationship between each pair of factors was bivariate and/or that they nonlinearly enhanced each other in influencing dust events; this was especially true for meteorological factors and LU (Fig. 6). Among the interactions of meteorological and anthropogenic factors, q (RH ∩ LU) was the maximum (0.32), indicating that the interaction between RH and LU was strongest, followed by the interactions between air pressure (MP, LP, and HP) and LU.

There were large seasonal variations in the interactions between each pair of factors (Fig. 7). In spring, the interactions between air pressure (LP, HP, and MP) and LU were strongest among all the interactions (Fig. 7a). All the top 20 interactions were between air pressure and potential impacting factors, indicating that air pressure played a dominant role in the occurrence of dust events in spring. The largest interaction was between CUL and LU in summer (Fig. 7b), and interactions between LU and other factors had greater contributions to dust events than other interactions. In autumn, however, the strongest interaction was between LU and GDP, with GDP having more influence, judging from its interactions with other factors (Fig. 7c). In winter, the interaction between LP and FP was largest (Fig. 7d). Moreover, the interactions between FP and meteorological conditions and between GDP and meteorological factors had larger impacts on dust events than

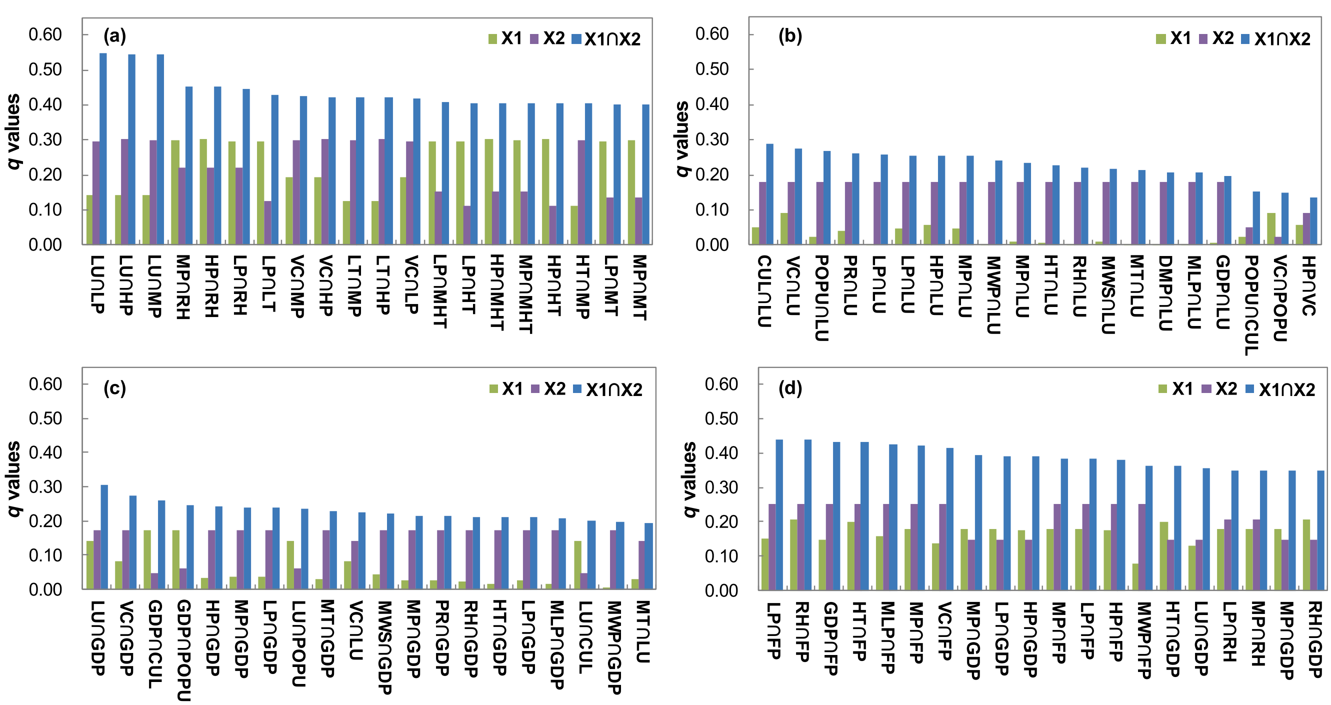

Fig. 7. The q values of the interactions between potential factors at the regional scale in spring (a), summer (b), autumn (c), and winter (d).

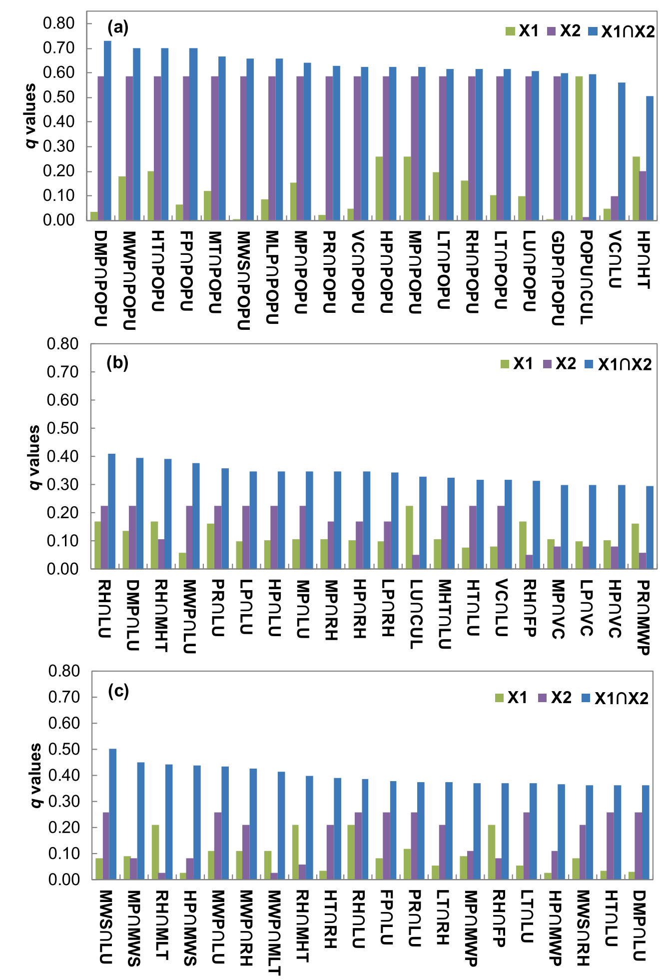

Fig. 8. Comparisons of the interactive q value and the original q value of each pair of factors in vegetation types: (a) deserts, (b) cultivated vegetation, and (c) steppes.

all the other interactions in winter (Fig. 7d).

3.3.2. Interactions in regions of different vegetation types

The interaction q value of each pair of factors presented large variations in the three vegetation-type regions (Fig. 8). In desert regions, the interaction between DMP and POPU was strongest among all the interactions, while the interaction between HT and HP was the strongest among the interactions between meteorological factors. The top 17 pair of interactions all included the POPU factor, which also indicated that POPU was an important factor in the occurrence of dust events in desert areas (Fig. 8a). In cultivated vegetation regions, the interaction between RH and LU was strongest among all the interactions between meteorological factors and anthropogenic factors (Fig. 8b). In steppe regions, however, the interaction between MWS and LU was largest, followed by the interaction between MP and MWS and between RH and MLT (Fig. 8c).

4. Discussion

Dust events are driven by natural and anthropogenic factors and their interactions. Previous studies have reported that dust events are associated with both meteorological and anthropogenic conditions (Wang et al., 2013; Csavina et al., 2014; Feng et al., 2017; Ju et al., 2018). This study quantified the influences of natural and anthropogenic factors, as well as of their interactions, on dust events using the GeoDetector q statistic. This method is capable of identifying the relative importance of various factors and their interactions in the occurrence of dust events. Being able to identify and quantify these factors can help to improve the performance of dust prediction models.

At the regional scale, we found that land use and relative humidity are the two dominant factors influencing dust events at the annual time scale. Among all the interactions, the interaction between relative humidity and land use presented the largest influence on dust events. This is because the land use change can affect the relative humidity (Mavrakis and Hr, 2013) and baseflow (Huang et al., 2020), thus affecting the surface soil moisture and the threshold friction velocity (Ravi et al., 2004; Ju et al., 2018) and then the occurrence of dust events. To control desertification, many ecological restoration programs (Zhang et al., 2018) have been conducted in China over the past several decades. The vegetation restoration (Xu et al., 2020) and its interaction with relative humidity (Mavrakis and Hr, 2013) is one of the reasons for the reduction of dust events in recent decades.

In spring, meteorological conditions, especially the air pressures and temperatures, were found to play dominant roles in the occurrence of dust events, which is consistent with previous studies (Csavina et al., 2014; Song et al., 2017; Namdari et al., 2018). The pressure gradient force and changes in the pressure at ground level have large influences on the wind speed in the near-surface layer (An et al., 2018). Strong winds and dry surface conditions due to higher temperatures could result in high frequencies of dust event (Kim et al., 2017; Shi et al., 2020). However, anthropogenic factors appear to be the primary influencing factors in summer and autumn. This is due to the intensity of human activities of grazing and mowing in these reasons can significantly influence the vegetation cover the soil surface conditions (Du et al., 2019; Shao et al., 2012; Wang et al., 2020). In winter, the frozen period and relative humidity were primary influencing factors, which can be explained that the relative humidity can impact dust events by influencing the soil moisture content and soil frozen period (Ravi et al., 2004; Wang et al., 2014; Ju et al., 2018). This is consistent with previous studies that have reported a slightly negative correlation between the relative humidity and dust concentrations, as well as dust fluxes (Ju et al., 2018). The frozen period can suppress/stimulate dust events, thus one of the main reasons for dust events occurring in spring and early summer is the long-term drying and freezing in winter, which makes the surface soil loose when it thaws in spring.

In desert regions, we found that population density was the primary impacting factor at the annual time scale. Air pressures were primary factors in spring over desert regions. This is because the pressure gradient force at the ground level have large influences on the wind speed near the surface (An et al., 2018), which provides the necessary dynamic conditions for dust emissions and transport. In summary, human activities, dry surface conditions, and strong winds were the main drivers of dust events in spring in desert regions, which is consistent with the results reported by previous studies (Kurosaki and Mikami, 2003; Gong et al., 2006; Kimand and Kai, 2007; Wang et al., 2019). However, wind speed does not work alone to generate dust events, but acts in combination with other factors such as vegetation coverage, soil moisture, and topography. The dominant factors are the land use and GDP in summer and autumn, respectively. This is because grazing and mowing intensity is significantly correlated with GDP (Wei and Zhen, 2020) and can significantly affect the vegetation productivity (Tälle et al., 2016; Chi et al., 2018), thus influencing the occurrence of dust events. Flourishing vegetation prevents dust emissions and thereby reduces the frequency of dust events (Rashki et al., 2013; Xu and Liao, 2007).

Land use and vegetation cover were major factors impacting dust events in steppe areas in spring. This is because vegetation can anchor the topsoil thereby preventing dust erosion (Kimura et al., 2009; Yan et al., 2011; Wang et al., 2013; Guan et al., 2017). In the steppe region of Inner Mongolia, mowing and grazing are two widely adopted practices for grasslands utilization and management (Shao et al., 2012, 2017) and are main contributors to GDP. GDP can be considered as an indicator of the mowing intensity, which suggests that the mowing intensity may be the primary driver of dust events in autumn. In summer, intense grazing can reduce grassland productivity and lead to desertification and then high dust emissions (Tong et al., 2004). In winter, the mechanism of dust events is more complex and mainly determined by the combined effects of wind velocity, relative humidity, lowest temperature, GDP, and vegetation cover. Furthermore, excessive grazing and mowing in spring, summer, and autumn could exacerbate the generation of dust events in winter. In cultivated vegetation regions in Northern China, similar to the steppe region, land use is the primary impacting factor throughout the whole year. The main crops in cultivated regions are wheat, maize, and potatoes, and all of them are planted in spring and harvested in autumn. The higher dust event frequency in spring can be attributed to the high wind speed and the bare soil surface in cultivated regions.

Wind erosion is affected by complex interactions among soil properties, climate, vegetation, and land management (Song et al., 2017). Complex interactions universally exist in the system of dust event generation. It is important to identify how natural and anthropogenic factors interact with each other because these results represent information useful for controlling and predicting the occurrence of dust events. The interaction detector revealed that interactions between all the factors presented enhanced influence on dust events. As the anthropogenic factors were related to human activities, such as grazing, mowing, and agriculture activities, their interactions would reinforce each other in exacerbating dust events. Anthropogenic activities, both spatially and seasonally, interact with natural fators within a vegetation system to further influence dust events.

5. Conclusions

This study found that the land use policy is one of the reasons resulting in the significant decrease of dust event frequency over the past several decades. Results revealed spatial and temporal variations in the impacts of natural and anthropogenic factors and their interactions on the occurrence of dust events. The combination of strong winds and dry surface conditions leads to the high frequency dust events in spring. Human activities such as grazing and mowing can significantly influence the occurrence of dust events in summer and autumn, but FP and RHU are the two major impacting factors in winter. The relative importance of impacting factors in dust events varies greatly in different vegetation type regions. Interactions between two influencing factors enhanced their impacts on dust event generation, and the dominant interaction factor affecting dust events differed at different vegetation regions and seasons.

Due to the complicated mechanisms and interactions between natural and anthropogenic factors, it remains challenging to understand the relative importance of impacting factors and their interactions in occurrence of dust events. This study comprehensively quantified the influences of natural conditions and anthropogenic factors and their interactions on dust events using the GeoDetector model in Northern China. Considering the difficulty in understanding quantitatively the association and the interaction between dust events and its impacting factors, these findings could help us to better understand the relative importance of impacting factors in the occurrence of dust events, and they have significant implications for the prediction of dust emissions. Moreover, these findings could guide the development of strategies for dust emission control and desertification mitigation in different vegetation regions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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