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Impact of Land-Use and Land-Cover Change on urban air quality in representative cities of China

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ABSTRACT

The atmospheric particulate pollution in China is getting worse. Land-Use and Land-Cover Change (LUCC) is a key factor that affects atmospheric particulate pollution. Understanding the response of particulate pollution to LUCC is necessary for environmental protection. Eight representative cities in China, Qingdao, Jinan, Zhengzhou, Xi'an, Lanzhou, Zhangye, Jiuquan, and Urumqi were selected to analyze the relationship between particulate pollution and LUCC. The MODIS (MODerate-resolution Imaging Spectroradiometer) aerosol product (MOD04) was used to estimate atmospheric particulate pollution for nearly 10 years, from 2001 to 2010. Six land-use types, water, woodland, grassland, cultivated land, urban, and unused land, were obtained from the MODIS land cover product (MOD12), where the LUCC of each category was estimated. The response of particulate pollution to LUCC was analyzed from the above mentioned two types of data. Moreover, the impacts of time-lag and urban type changes on particulate pollution were also considered. Analysis results showed that due to natural factors, or human activities such as urban sprawl or deforestation, etc., the response of particulate pollution to LUCC shows obvious differences in different areas. The correlation between particulate pollution and LUCC is lower in coastal areas but higher in inland areas. The dominant factor affecting urban air quality in LUCC changes from ocean, to woodland, to urban land, and eventually into grassland or unused land when moving from the coast to inland China.

1. Introduction

Atmospheric particulate matter comprises colloids of solid particles or liquid droplets suspended in the atmosphere; the diameters of these particles or droplets range from 0.001 to 20 μm. With the rapid development of China's economy, atmospheric particulate pollution is escalating, which significantly affects economic development and people's lives (Brunekreef and Holgate, 2002). In particular, PM_{10} and $PM_{2.5}$, having particulate aerodynamic diameters of less than 10 and 2.5 μm, can easily enter the lungs, and being enriched with organic pollutants and viruses, can cause serious harm to human health (Colvile et al., 2001; Brunekreef and Holgate, 2002; Xu, 2002; Espinosa et al., 2002; Marcazzan et al., 2003; Kocifaj et al., 2006; Huang et al., 2012). Atmospheric particulate matter can also lead to a poor atmospheric visibility by absorbing and scattering light (Wang et al., 2009; Chen et al., 2010; Han et al., 2011).

Research on Land-Use and Land-Cover Change (LUCC) using remote sensing technology has a long history and has made progress (Singh, 1989; Jensen, 1996; Coppin et al., 2004; Lu et al., 2004; Liu et al., 2008; Dewan and Yamaguchi, 2009a, 2009b; Dewan et al., 2012; Wei et al., 2015). LUCC is an important indicator in understanding the interactions between human activities and the environment (Dewan et al., 2012). In recent years, land cover has changed rapidly in developing nations, particularly in China (Wu et al., 2008; Zeng et al., 2014; Liu et al., 2014; Güneralp et al., 2015). The rapid changes of land cover are often characterized by urban sprawl (Mundia and Aniya 2006; Jat et al. 2008; Dewan and Yamaguchi 2009b; Dewan et al., 2012; Dewan, 2012; Byomkesh et al., 2012; Liu et al., 2014), farmland displacement (Ali, 2006; Du et al., 2013), and deforestation (Zhang and Song, 2006), leading to the loss of arable land (Lopez et al., 2001), habitat destruction (Alphan, 2003), and the decline of the natural greenery areas (Swanwick et al. 2003; Kong and Nakagoshi 2006). These losses have a substantial impact on urban environmental conditions such as biodiversity, climate change, and atmosphere particulate pollution at local and/or global scales (Nagendra et al., 2004; Phan and Nakagoshi, 2007).

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Researchers have conducted numerous studies on atmospheric particulate pollution. Related studies on atmospheric particulate pollution have mainly focused on its spatial and temporal distribution (Li et al., 2003, 2005; Fan et al., 2011; Chen et al., 2013; Sun et al., 2016), health effects (Samet et al., 2000; Brunekreef and Holgate, 2002; Nemmar et al., 2003; Dominici et al., 2006; Zhang et al., 2006;

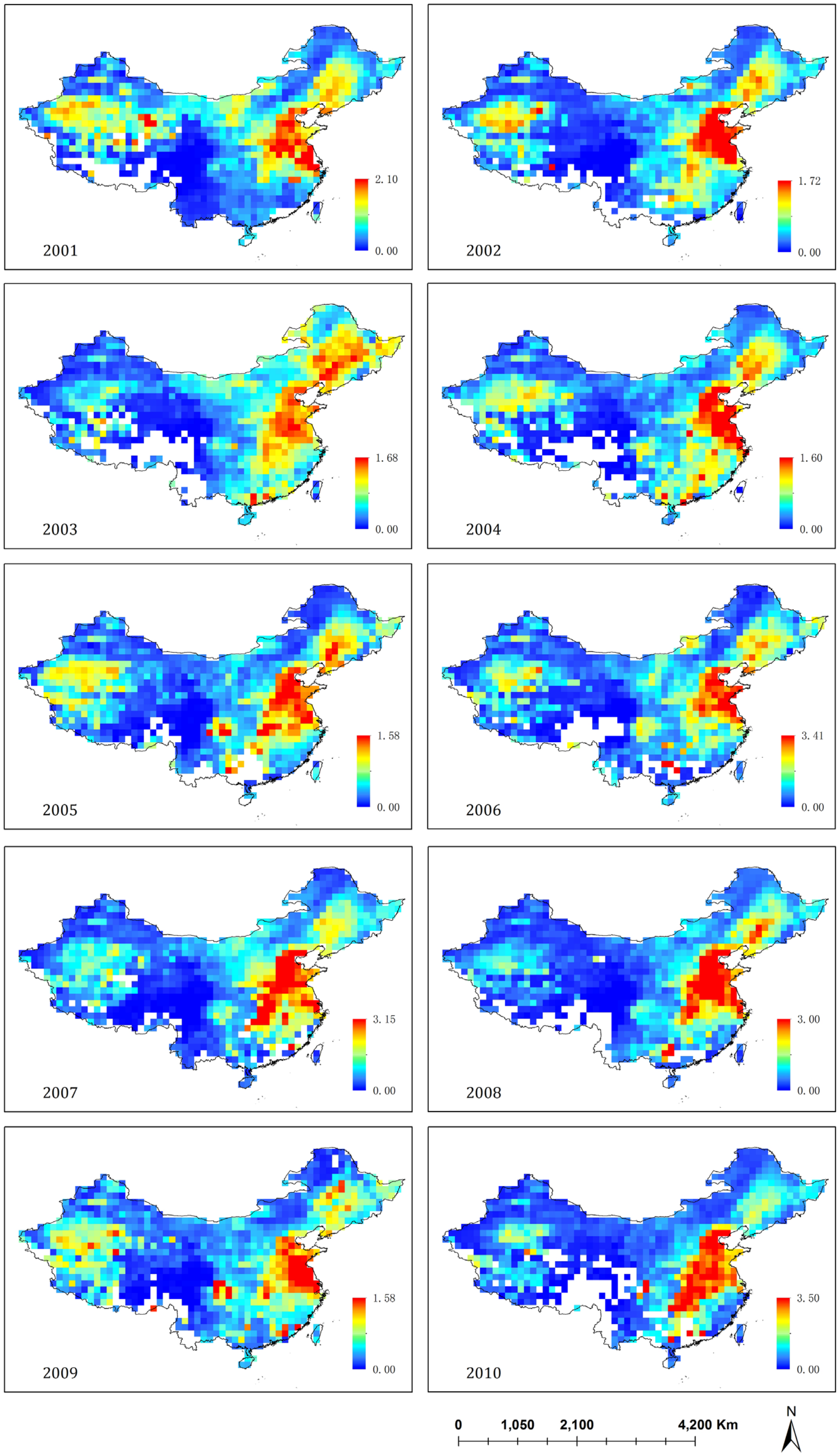

Fig. 1. Aerosol optical depth (AOD) spatial distribution of China in June from 2001 to 2010.

Li, 2011), near-surface particulate concentration conversion (Lau et al., 2003; Wang and Christopher, 2003; Gupta et al., 2006, 2007; Liu et al., 2007; Gupta and Christopher, 2008), correlation analysis between aerosol optical depth (AOD) and particulates (Gupta et al., 2006, 2007; Gupta and Christopher, 2008), and dust or haze impact (Shi et al., 2010; Feng et al., 2010, 2011). Obtaining a deeper understanding of the response mechanism of urban particulate pollution has an important practical significance in preventing pollution and protecting ecological environment; however, such studies are relatively few and have rarely been investigated (Wei et al., 2015). Many factors could cause particulate pollution, such as construction dust, domestic garbage, and vehicle exhaust, but most pollution can be reflected by land use changes. This paper aims to investigate the effect of LUCC on the particulate pollution in urban areas.

With the development of satellite remote sensing, LUCC and particulate matter information over long time series can be easily obtained from the current products of multi-source remote sensing data. Eight representative urban areas from east to west in China, which also represent the distance from coast to inland areas, were selected to research the relationship between particulate pollution and LUCC. The urban particulate pollution data were obtained from the MODIS AOD product (MOD04), and the LUCC data at corresponding times were extracted from the MODIS land cover product (MOD12) for the period 2001–2010. The MODIS products are obtained from the GSFC (Goddard Space Flight Center) Level 1 and Atmosphere Archive and Distribution System (LAADS) (〈http://ladsweb.nascom.nasa.gov〉).

2. Description of study area

China is in middle-eastern Asia, which is bounded by the sea in the east and by deep inland areas in the west. Different terrains and climates cause obvious differences in land cover distributions. For example, woodland areas are mainly located in the southeast coast and northeast region, and grassland (mainly unused land) are located in the west and southwest regions.

Fig. 1 shows the AOD spatial distribution of China in June for the period 2001–2010. From Fig. 1, the spatial distribution and variation of aerosol in summer in China for nearly 10 years can be observed. The AOD is overall larger, which shows more serious atmospheric particulate pollution in China. East China has a higher AOD distribution and the air pollution is more serious; however, the AODs are relatively lower in central and western China, showing an overall lighter air pollution. The inter-annual range distribution and variation of AODs are more changeable and unstable in different regions with larger fluctuations. However, there are some differences of air pollution in different regions.

Concerning cities selection, eight representative cities in China, Qingdao, Jinan, Zhengzhou, Xi'an, Lanzhou, Zhangye, Jiuquan, and Urumqi, that follow a relatively continuous distance from the coastal areas to the inland areas located at a similar latitude belt (Latitude ~34° to 44°N) are selected as the experiment areas. These cities are obviously different in climate, economy and land use sources. Fig. 2 shows the spatial distribution of the eight representative cities in China. Qingdao is located in the eastern coastal areas of China and is significantly affected by the ocean. Jinan is in the west, is the capital of Shandong province and has a dense population. Both Zhengzhou and Xi'an are the typical cities in the middle of China with developed economies. Lanzhou, Zhangye, Jiuquan and Urumqi are the typical western cities in China with a continental arid climate.

3. Data and methods

3.1. Data acquisition and preparation

Atmospheric particulate pollution and LUCC data of eight cities in China from 2001 to 2010 were obtained. Fig. 3 shows the main steps of the response of particulate pollution to LUCC in Chinese areas.

Atmospheric particulate pollution is obtained from the MOD04 aerosol product. MOD04 is produced by NASA from the MODIS level 2 product and monitors seven wavelengths that include 470, 550, 659, 865, 1240, 1640 and 2130 nm with a spatial resolution of

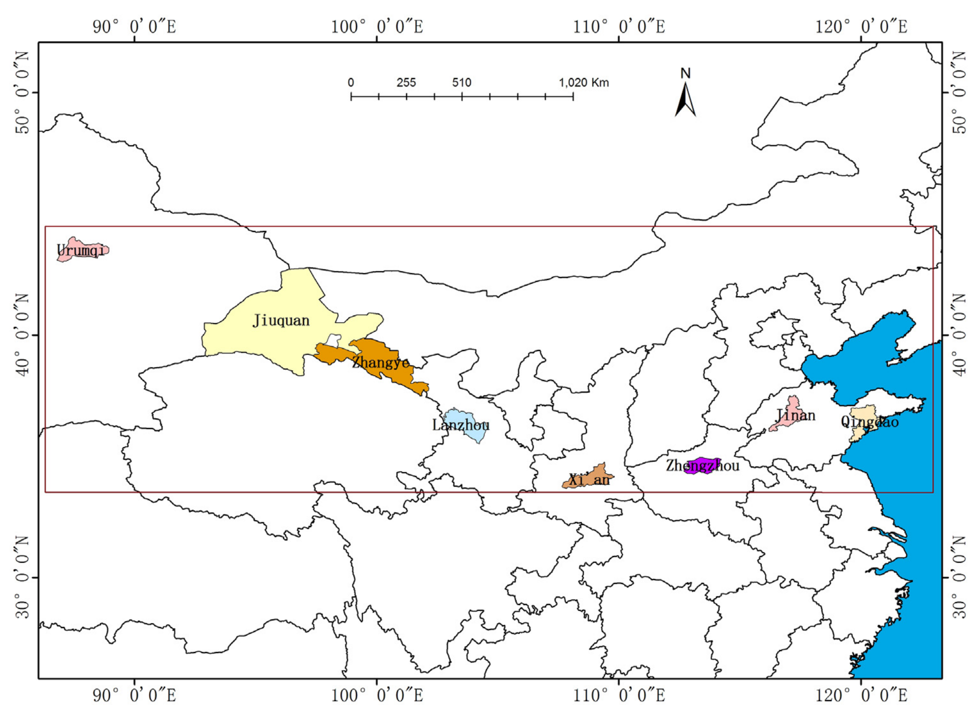

Fig. 2. Location of the study areas.

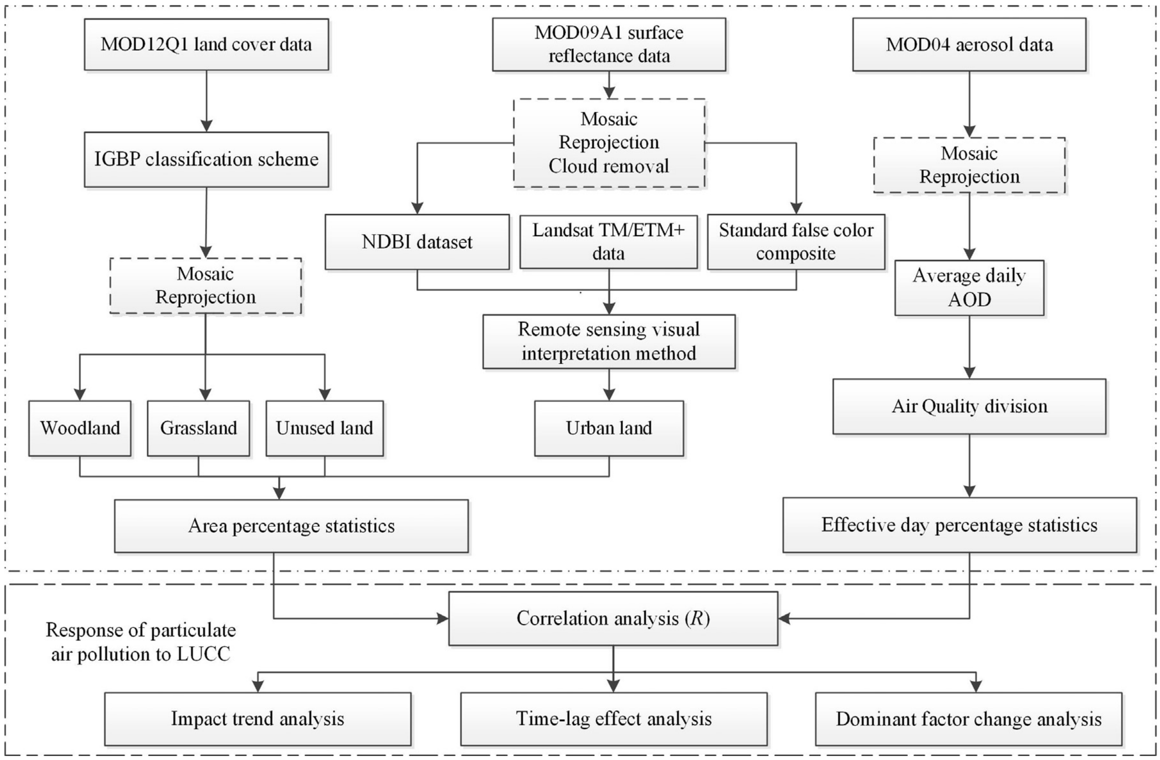

Fig. 3. Major steps of the response of particulate pollution to LUCC in Chinese areas.

10 km. The MOD04 product has been validated in different areas, has proved of high level of precision, and has been widely applied to climate change research and environmental quality monitoring so forth (Li et al., 2003, 2005; Wang and Christopher, 2003; Shi et al., 2010). The current MOD04 aerosol product has Collection 5.1 (C5) and 6 (C6) versions. The C6 version contains the DB (Deep Blue) aerosol retrieval algorithm, which includes AOD retrieval for all dark and bright surfaces (including cities, arid areas, and even deserts). The latest research showed that the DB C6 is able to retrieve AOD well compared with AERONET measurements during both clear and turbid days and has lower retrieval uncertainty than the DT (Dark Target) aerosol retrieval algorithm (Hsu et al., 2006, 2013; Bilal and Nichol, 2015). AODs in eight areas in the summer from 2001 to 2010 are extracted from the MOD04 C6 product to analyze the changes in particulate matter concentration.

LUCC information was extracted from the MODIS annual land use cover product (MOD12Q1). MOD12Q1 is mainly based on the International Geosphere-Biosphere Program (IGBP) classification system that obtains a classification algorithm of decision tree and artificial neural network (Wei and Wang, 2010). It is an important data source and has been extensively applied to monitor LUCC dynamics. Research on the accuracy evaluation of MOD12Q1 has shown that it has a higher overall classification accuracy for woodland, grassland, cultivated land, bare land and water, but a lower accuracy for urban land and wetland (Wu et al., 2009; Liu et al., 2012; Yang et al., 2014). Hence the MOD12Q1 product was selected to extract the land types with a higher accuracy, yet for the urban land extraction, the surface reflectance product, MOD09A1 (MODIS 8-day synthetic gridded level-3 product), was used.

3.2. Information extraction of particulate pollution and LUCC

To compare the particulate distribution in different areas, the mean value of AODs was calculated first with the following equation:

$$AOD_{avg}=\left[\sum_{i=1}^{m}\sum_{j=1}^{n}(AOD(i,j))\right]/N \tag{1}$$

where AOD_{avg} is the average daily *AOD*, *AOD (i, j)* is the pixel value of row *j* and column *i*, and *N* is the total number of effective pixels (where $N=m^{*}n$).

With consideration of the correlation between atmospheric visibility (*V*) and air pollution, visibility is divided into the following four levels: (1) when *V* exceeds 10 km, particulate pollution was marked as "no pollution" (2) when *V* is between 5 and 10 km, it was marked as "slight pollution" (3) when *V* is between 2.5 and 5 km, it was marked as "medium pollution" and (4) when *V* is less than 2.5 km, it was marked as "heavy pollution". Particulate pollution was calculated based on visibility using the empirical formula that Koschmieder (Koschmieder 1924; Sheng et al., 2009) proposed,

$$\mathrm{AOD}_T=\frac{3.91H}{V} \tag{2}$$

where *H* is the elevation (km) obtained from the Digital Elevation Model (DEM) and AOD_T is the AOD threshold.

The above visibility *V* can be directly related with AODs, and Table 1 lists the average daily *AOD* segmentation. The total days for each air pollution level were counted, and the effective percentages were also calculated accordingly (Table 2).

Table 1
Air quality division standards.

Level	Atmospheric visibility (*V*)	AOD_T	Description
I	$V > 10$ km	≤ 0.3	No pollution
II	$5 < V \leq 10$ km	0.3–0.5	Slight pollution
III	$2.5 < V \leq 5$ km	0.5–1.5	Medium pollution
IV	$V \leq 2.5$ km	> 1.5	Heavy pollution

Table 2 displays the effective day statistics of different air pollution levels in representative cities of China from 2001 to 2010. Qingdao, Jinan, Zhengzhou and Xi'an are four typical central and eastern cities with developed economies and dense populations and that showed heavy air pollution, having less than 30% of no pollution days in the whole year. However, there are more than 50% of no pollution days in Lanzhou and, in recent years, 80% in Zhangye, Jiuquan and Urumqi, indicating an overall better air quality in these cities.

The data processing for the LUCC data mainly includes re-projection and class merge. The land cover types in MOD12Q1 are divided into six classes, water, woodland, grassland, cultivated land, urban land, and unused land, according to the Chinese classification system. According to previous research (Wu et al., 2009; Liu et al., 2012; Yang et al., 2014), water, woodland, grassland, cultivated land and unused land classes were obtained from MOD12Q1 data. Urban land has a relatively small area and is easily affected by the surrounding terrain; therefore, the visual interpretation method with Normalized Difference Build-up Index (NDBI) and higher resolution images were applied to help extract urban land to improve the overall classification accuracy.

Clear images for urban land extraction were obtained from MOD09A1 data with the minimum value synthesis technology, which can effectively remove the cloud pollution in remote sensing images. NDBI was calculated to highlight the urban land information with the following equation:

$$NDBI = \frac{R_{SWIR} - R_{NIR}}{R_{SWIR} + R_{NIR}} \quad (3)$$

where R_{SWIR} and R_{NIR} are the shortwave-infrared and near-infrared spectral reflectance, which correspond to the band 6 and band 2 of MODIS, respectively. Table 3 displays the area statistics of different land use types in representative cities of China from 2001 to 2010.

For four central and eastern coastal cities in China, Qingdao, Jinan, Zhengzhou and Xi'an, the main land use types are woodland and urban land, which shows an overall increasing trend over the last 10 years. For the four deep inland cities, Lanzhou, Zhangye, Jiuquan and Urumqi, they are mainly composed of grassland and unused land. More than 60% of land resources are classified as grassland in Lanzhou (actually more than 90%), Zhangye and Urumqi and 90% for unused land in Jiuquan. However, different cities showed obvious different LUCC in recent 10 years.

The Pearson Product-moment Correlation Coefficient (PPCC, referred to as "R"), which is currently widely applied in various scientific fields, was selected to analyze the correlation between LUCC and particulate pollution. The correlation coefficient (R) is calculated as follows:

$$R = \frac{\Sigma_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\Sigma_{i=1}^{n}(x_i - \bar{x})^2 \Sigma_{i=1}^{n}(y_i - \bar{y})^2}} \quad (4)$$

4. Results and discussion

4.1. Impact of LUCC on particulate pollution

The effects of LUCC on particulate pollution in the eight areas in China are investigated by calculating the current correlation between particulate pollution and LUCC (Table 4), and Figs. 4–6 show the air pollution variation along with LUCC in the different areas.

LUCC shows low influences on particulate pollution in Qingdao; the correlation is generally lower than the other areas (Table 4). Woodland and low pollution days (levels I and II) have displayed an increasing trend in recent years (Fig. 4a). The variation trend of woodland is more consistent with level II (R=0.570), but substantially contradictory with high-pollution days (levels III and IV) (R=−0.459, −0.137). As a coastal city, Qingdao is significantly affected by the ocean, and the southeast monsoon dominates in summer, reducing the pollutants in the air and resulting in a low correlation between LUCC and particulate pollution.

Urban land shows a more obvious impact on particulate

Table 2
Effective day statistics of different air pollution weather in representative cities of China from 2001 to 2010.

Percentage statistics	Qingdao				Jinan				Zhengzhou				Xi'an			
	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV
2001	32.56	53.49	11.63	2.33	15.09	71.70	11.32	1.89	12.00	52.00	32.00	4.00	28.26	60.87	10.87	0.00
2002	31.15	36.07	27.87	4.92	22.39	28.36	40.30	8.96	17.46	30.16	44.44	7.94	21.43	60.00	18.57	0.00
2003	35.85	32.08	18.87	13.21	9.43	45.28	33.96	11.32	12.77	40.43	27.66	19.15	30.00	54.00	16.00	0.00
2004	31.25	45.83	22.92	0.00	29.82	42.11	24.56	3.51	14.55	41.82	41.82	1.82	32.76	56.90	10.34	0.00
2005	25.49	50.98	17.65	5.88	20.00	51.67	16.67	11.67	13.21	52.83	33.96	0.00	27.78	64.81	7.41	0.00
2006	50.94	26.42	18.87	3.77	8.20	59.02	24.59	8.20	9.80	52.94	33.33	3.92	19.30	43.86	26.32	10.53
2007	25.49	50.98	11.76	11.76	11.76	41.18	37.25	9.80	11.76	45.10	29.41	13.73	26.92	42.31	26.92	3.85
2008	22.22	57.78	15.56	4.44	16.67	41.67	33.33	8.33	10.87	50.00	32.61	6.52	30.61	48.98	16.33	4.08
2009	33.85	55.38	9.23	1.54	34.38	43.75	14.06	7.81	21.43	55.36	17.86	5.36	45.61	42.11	10.53	1.75
2010	21.43	54.76	19.05	4.76	20.00	47.50	17.50	15.00	7.55	58.49	28.30	5.66	23.53	58.82	15.69	1.96
Percentage statistics	Lanzhou				Zhangye				Jiuquan				Urumqi			
	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV
2001	54.17	41.67	4.17	0.00	86.44	13.56	0.00	0.00	78.00	20.00	0.00	2.00	80.85	19.15	0.00	0.00
2002	54.55	42.42	3.03	0.00	91.78	8.22	0.00	0.00	81.94	16.67	1.39	0.00	75.00	25.00	0.00	0.00
2003	50.00	46.55	3.45	0.00	81.58	17.11	1.32	0.00	71.88	26.56	1.56	0.00	80.26	19.74	0.00	0.00
2004	52.63	47.37	0.00	0.00	90.28	8.33	1.39	0.00	76.56	20.31	1.56	1.56	90.14	9.86	0.00	0.00
2005	47.83	52.17	0.00	0.00	91.55	8.45	0.00	0.00	84.51	15.49	0.00	0.00	89.86	10.14	0.00	0.00
2006	51.79	48.21	0.00	0.00	88.24	11.76	0.00	0.00	86.76	13.24	0.00	0.00	88.57	11.43	0.00	0.00
2007	37.04	61.11	1.85	0.00	83.33	16.67	0.00	0.00	84.38	12.50	1.56	1.56	90.14	9.86	0.00	0.00
2008	46.03	50.79	3.17	0.00	93.75	6.25	0.00	0.00	83.78	14.86	1.35	0.00	86.84	13.16	0.00	0.00
2009	76.92	23.08	0.00	0.00	90.79	9.21	0.00	0.00	87.14	12.86	0.00	0.00	86.25	13.75	0.00	0.00
2010	69.23	30.77	0.00	0.00	89.33	9.33	1.33	0.00	83.82	14.71	1.47	0.00	79.03	20.97	0.00	0.00

I represents no pollution days, II represents slight pollution days, III represents medium pollution days and IV represents heavy pollution days.

Table 3
Area statistics of different land use types in representative cities of China from 2001 to 2010.

Percentage statistics	Qingdao				Jinan				Zhengzhou				Xi'an			
	Woodland	Grassland	Urban land	Unused land	Woodland	Grassland	Urban land	Unused land	Woodland	Grassland	Urban land	Unused land	Woodland	Grassland	Urban land	Unused land
2001	1.04	7.44	7.87	0.54	1.65	6.13	4.65	0.09	0.51	15.39	2.93	0.19	45.98	3.66	3.46	0.01
2002	0.72	5.96	7.34	0.86	1.07	4.47	4.60	0.07	0.75	6.33	4.62	0.11	45.31	1.92	4.32	0.00
2003	0.89	5.60	10.35	0.73	1.27	3.20	5.79	0.05	0.82	5.39	3.84	0.04	45.40	1.12	2.63	0.00
2004	0.93	4.54	9.48	1.09	1.37	2.26	5.70	0.07	0.99	2.38	4.77	0.06	45.01	1.09	3.69	0.00
2005	1.30	4.57	10.02	0.55	1.70	1.88	5.47	0.07	1.13	3.24	5.71	0.04	46.59	1.34	4.60	0.00
2006	1.30	5.02	10.19	0.91	2.17	2.29	5.65	0.07	1.33	2.70	5.99	0.09	46.91	1.88	4.85	0.00
2007	1.48	5.53	10.00	0.66	2.09	3.15	5.74	0.03	1.27	3.42	5.95	0.07	47.37	1.73	4.00	0.00
2008	2.05	6.51	10.69	0.85	3.03	3.47	6.14	0.02	1.36	3.49	9.67	0.11	47.62	1.31	6.84	0.00
2009	1.95	5.02	10.29	0.54	2.93	2.11	6.25	0.02	1.35	2.88	6.03	0.07	48.12	0.93	6.71	0.00
2010	2.23	5.84	10.77	0.49	2.81	3.15	6.46	0.02	1.72	2.59	12.26	0.10	48.55	0.94	10.14	0.00

Percentage statistics	Lanzhou				Zhangye				Jiuquan				Urumqi			
	Woodland	Grassland	Urban land	Unused land	Woodland	Grassland	Urban land	Unused land	Woodland	Grassland	Urban land	Unused land	Woodland	Grassland	Urban land	Unused land
2001	0.78	94.76	1.24	0.19	0.79	61.78	0.01	34.42	0.00	4.24	0.00	94.70	2.07	85.18	1.42	7.29
2002	0.45	94.85	1.29	0.04	0.52	64.13	0.01	31.46	0.00	4.23	0.00	94.67	2.06	84.78	1.63	6.95
2003	0.45	95.35	1.12	0.01	0.51	65.62	0.00	30.19	0.00	5.00	0.01	93.71	2.07	80.00	1.57	11.79
2004	0.42	94.69	1.31	0.01	0.46	66.38	0.01	28.68	0.00	5.41	0.01	93.16	2.17	72.16	1.56	19.73
2005	0.52	94.71	1.32	0.01	0.60	66.28	0.01	27.73	0.00	5.08	0.01	93.40	2.36	69.53	1.71	22.47
2006	0.64	94.77	1.31	0.02	0.67	66.16	0.01	28.08	0.00	6.43	0.01	92.02	3.49	67.34	2.03	24.21
2007	0.57	94.49	1.12	0.00	0.78	69.02	0.01	24.08	0.00	5.30	0.02	93.18	3.43	73.55	1.83	17.49
2008	0.66	94.60	1.75	0.00	0.83	69.47	0.03	24.52	0.00	4.75	0.02	93.70	3.70	66.11	2.23	24.79
2009	0.85	94.12	1.68	0.00	0.86	70.96	0.03	22.74	0.00	4.61	0.04	93.76	3.53	70.49	2.67	20.62
2010	0.85	94.21	2.50	0.00	0.93	69.53	0.07	23.73	0.01	3.96	0.01	95.07	4.29	67.39	3.48	23.45

Table 4
Current response of particulate matter pollution to LUCC in representative cities of China.

Areas	Qingdao				Jinan			
R	I	II	III	IV	I	II	III	IV
Woodland	−0.363	0.570	−0.459	−0.137	0.220	−0.055	−0.286	0.455
Grassland	−0.213	0.266	−0.220	0.033	−0.263	0.285	0.042	−0.400
Urban land	−0.273	0.421	−0.105	−0.308	−0.220	0.558	−0.327	0.041
Unused land	−0.356	−0.506	**0.594***	−0.197	–	–	–	–
Areas	Zhengzhou				Xi'an			
R	I	II	III	IV	I	II	III	IV
Woodland	−0.305	**0.596***	−0.418	−0.315	0.184	−0.450	0.164	0.403
Grassland	−0.006	−0.094	0.095	0.021	−0.318	0.221	0.071	−0.001
Urban land	−0.468	0.507	−0.225	−0.141	0.046	−0.081	−0.043	0.187
Unused land	–	–	–	–	–	–	–	–
Areas	Lanzhou				Zhangye			
R	I	II	III	IV	I	II	III	IV
Woodland	**0.638***	**−0.646***	−0.149	–	0.113	−0.071	−0.266	–
Grassland	−0.541	0.481	0.546	–	0.221	−0.239	0.058	–
Urban land	0.420	−0.453	0.081	–	–	–	–	–
Unused land	–	–	–	–	−0.221	0.230	−0.003	–
Areas	Jiuquan				Urumqi			
R	I	II	III	IV	I	II	III	IV
Woodland	–	–	–	–	0.197	−0.197	–	–
Grassland	0.480	−0.580	0.137	0.122	**−0.626***	**0.626***	–	–
Urban land	–	–	–	–	−0.122	0.122	–	–
Unused land	**−0.580***	**0.664***	−0.104	−0.008	**0.648***	**−0.648***	–	–

*At 0.05 level (double side) significantly correlated.

pollution in Jinan and has a higher correlation than Qingdao. Urban land displays an increasing trend and exhibits almost the same trend with level II (R=0.558) but the opposite trend with level I (R=−0.220). As the capital of Shandong province, due to rapid economic development, Jinan has shown faster urban sprawl and large vegetation areas have been replaced by city buildings over the last 10 years, leading to an increase in air pollution (Fig. 4b).

Woodland and urban land have a relatively obvious influence on particulate pollution in Zhengzhou, while the effect of woodland on particulate pollution is generally higher than urban land (Table 4). Woodland and urban land display an increasing trend, and the high-pollution days (levels III and IV) are decreasing and the low-pollution days (levels I and II) are increasing during the period of 2001–2010 (Fig. 5a). Urban land has the same trend with high pollution days, whereas woodland has an opposite trend with high pollution days (R=0.418, 0.315). Rapid urban sprawl has caused serious particulate pollution in the last 10 years; however, the increasing woodland area helps reduce the pollutants in the atmosphere and improves the air quality overall.

Vegetation restoration work (e.g., large-scale afforestation and transforming farmland to forest) has been conducted in Xi'an, initiating the rapid growth of woodland. The woodland exhibits a gradual increasing trend, whereas grassland shows the opposite

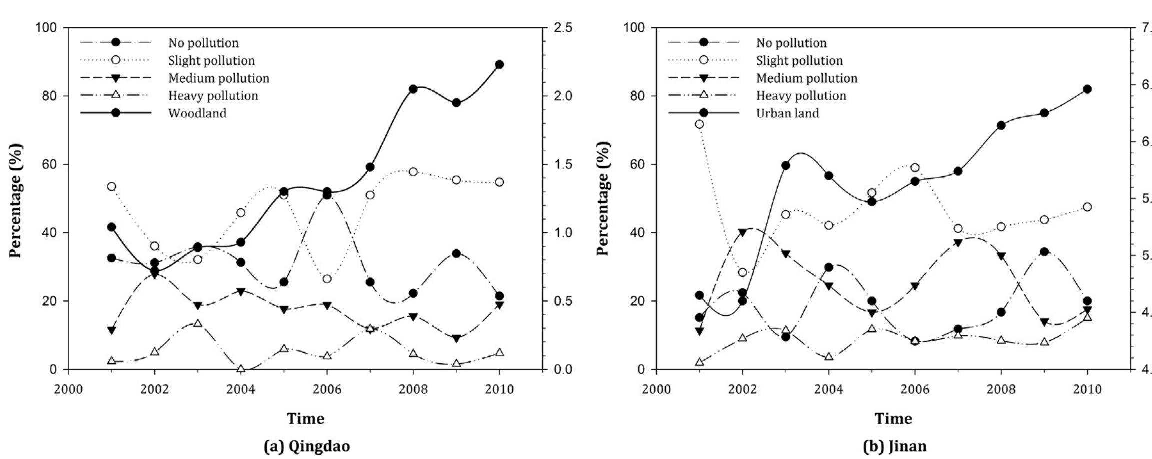

Fig. 4. Relationship between air pollution change and LUCC in eastern cities of China (a: Qingdao and b: Jinan).

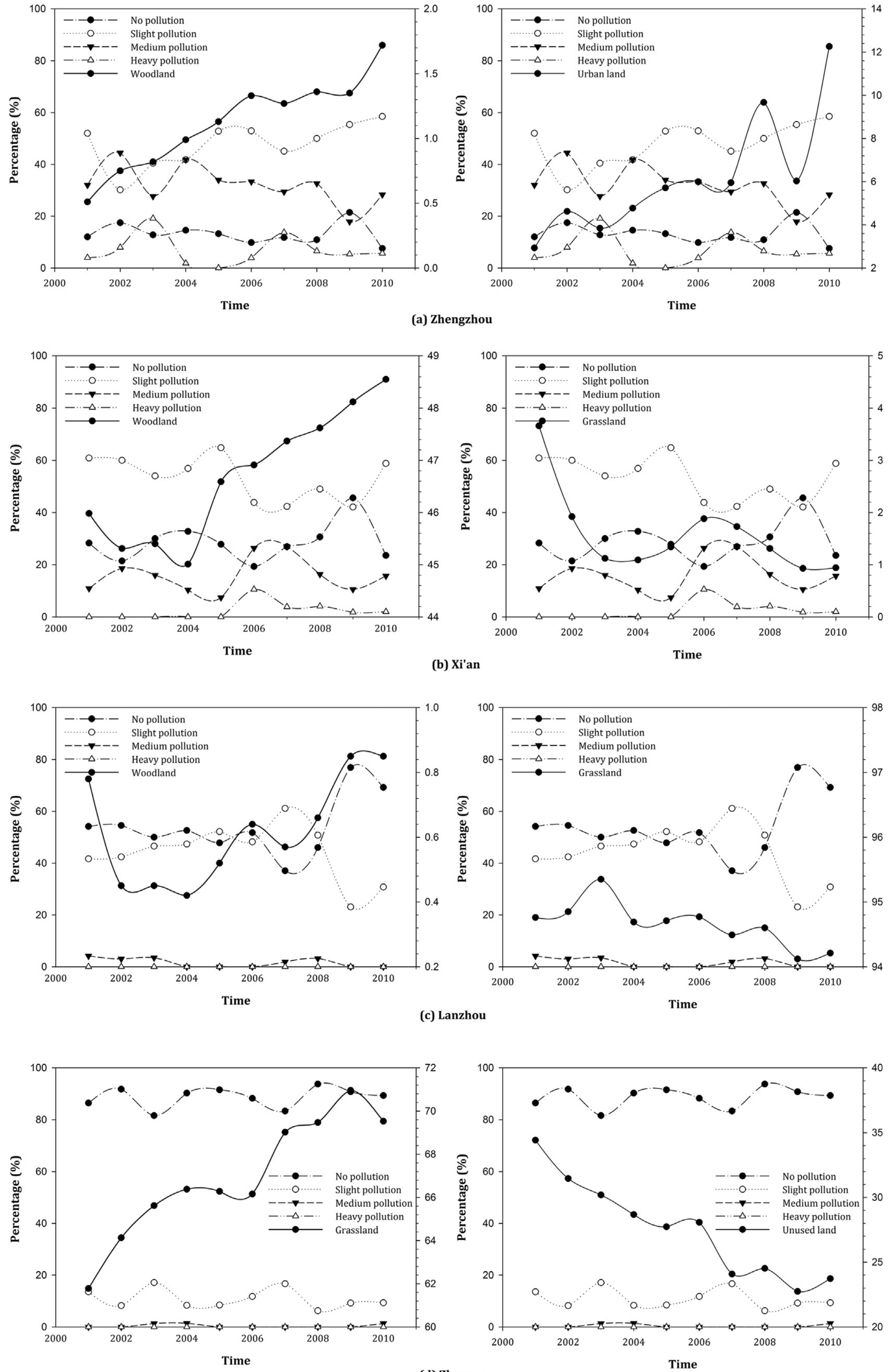

Fig. 5. Relationship between air pollution change and LUCC in central cities of China (a: Zhengzhou, b: Xi'an, c: Lanzhou and d: Zhangye).

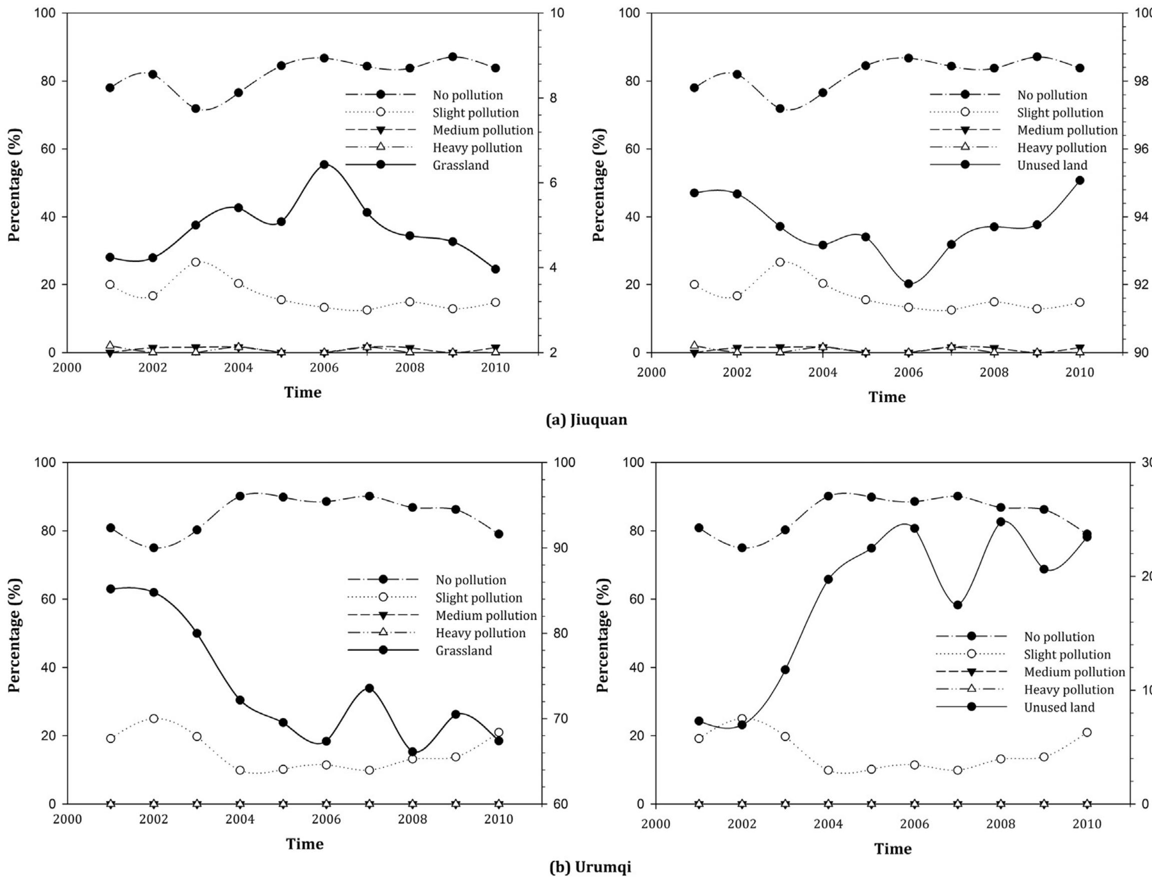

Fig. 6. Graph of air pollution change and LUCC in western cities of China (a: Jiuquan and b: Urumqi).

trend (Fig. 5b). Both the woodland and grassland have a relatively high correlation with particulate pollution in the city. However, the overall trend of particulate pollution is getting better.

Woodland exhibits an increasing trend, whereas grassland has a decreasing trend in Lanzhou (Fig. 5c). Both have an obvious effect on particulate pollution, and compared with grassland, woodland has a higher correlation. The variation trend of woodland is similar to no pollution days but contrary to slight pollution days ($R=0.638^*$, -0.646^*). Woodland has been rapidly increasing in recent years and effectively improved the urban air quality.

The response of particulate pollution to LUCC is relatively poor in Zhangye. Grassland exhibits an increasing trend, whereas unused land has a decreasing trend (Fig. 5d). Except for 2003 and 2007, grassland has a significant opposite trend with slight pollution days ($R=-0.239$) and a similar trend with no pollution days. However, the variation trend of unused land with particulate pollution is not obvious. This city mainly includes grassland and unused land, and the land use structure has significantly been changed in recent years. The large transformation of farmland and unused land to forest and grassland effectively improves the urban air quality under western development strategies.

Grassland showed a continuous decreasing trend and unused land showed the opposite trend after 2006 in Jiuquan, a typical city in west China. No pollution days showed an overall increasing trend in the last 10 years (Fig. 6a). Unused land showed a similar decreasing trend with the slight pollution days ($R=0.664^*$), but an opposite increasing trend with no pollution days. Grassland showed an obvious effect on urban particulate pollution and improved the air quality, while unused land showed the opposite effect.

Urumqi has the best air quality among the eight areas. Grassland and unused land have an obvious effect on urban air pollution according to the correlation between them. A decreasing trend is observed for grassland and an increasing trend for unused land, which deteriorates the urban air quality (Fig. 6b). Grassland shows a similar increasing trend with no pollution days ($R=-0.626^*$) and an opposite decreasing trend with slight pollution days since 2004. However, the effect of unused land on urban particulate pollution is opposite to that of grassland.

4.2. Time-lag effect of LUCC on particulate pollution

The response of LUCC to atmospheric particulate pollution may show a time-lag effect. When LUCC occurs in a short period of time due to natural disasters or human activities, it will show a smaller impact on existing urban air pollution but a bigger influence after a few years. Therefore, the correlation relationship between the current LUCC and the particulate pollution in the subsequent three years was calculated to perform the time-lag effect analysis of LUCC on particulate pollution (Table 5).

The impact of LUCC on particulate pollution in the subsequent three years in Qingdao is relatively low (Table 5). Woodland has a relative influence on particulate pollution in the subsequent three years, and the maximum influence appears one year later ($R=-0.278$, 0.608^*, -0.579). Urban land has a significant influence on particulate pollution in the subsequent three years in Jinan, and the maximum influence appears two years later ($R=-0.576$, 0.824^{**}, 0.007).

For four representative cities, Zhengzhou, Xi'an, Lan Zhou and Zhangye, in central China, woodland and urban land show obvious impacts on urban particulate pollution in the subsequent three years, and the maximum effect appears one year later (i.e., $R=-0.275$, 0.844^{**}, -0.711^* for woodland and $R=0.254$, 0.709^*, -0.899^{**} for

Table 5
Time-lag effect response of particulate matter pollution to LUCC in subsequent years in selected cities of China.

Air pollution level	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III
Areas	Qingdao									Jinan								
Correlation matrix	Woodland			Grassland			Urban land			Woodland			Grassland			Urban land		
Current year	−0.363	**0.570**	**−0.459**	−0.213	0.266	−0.220	−0.075	0.146	−0.322	0.220	−0.055	−0.286	−0.263	0.285	0.042	**−0.227**	**0.577**	−0.384
One year later	−0.278	**0.608***	**−0.579**	−0.011	−0.102	0.312	−0.078	0.557	−0.476	0.181	0.171	−0.441	0.214	−0.795	0.549	**−0.137**	**0.855****	−0.791**
Two years later	−0.470	**0.598***	**−0.423**	−0.152	−0.124	0.404	−0.316	0.458	−0.361	0.196	−0.257	−0.199	0.080	−0.152	0.006	**−0.576**	**0.824****	0.007
Three years later	−0.374	**0.565**	**−0.316**	0.193	−0.320	0.793**	0.365	−0.144	−0.502	0.407	−0.395	−0.286	0.330	0.123	−0.293	**−0.317**	**0.217**	0.105
Areas	Zhengzhou									Xi'an								
Correlation matrix	Woodland			Grassland			Urban land			Woodland			Grassland			Urban land		
Current year	−0.305	**0.596***	**−0.418**	−0.006	−0.094	0.095	−0.468	**0.507**	**−0.225**	**0.184**	**−0.450**	0.164	−0.318	0.221	0.071	0.046	−0.081	−0.043
One year later	−0.275	**0.844****	**−0.711***	**0.415**	**−0.852****	**0.596***	0.254	**0.709***	**−0.899****	**0.142**	**−0.510**	0.279	−0.297	0.095	0.320	0.299	−0.412	0.076
Two years later	−0.089	**0.721***	**−0.392**	0.087	−0.655*	−0.002	−0.329	**0.667***	**−0.254**	**0.383**	**−0.218**	−0.057	0.283	0.056	−0.156	−0.169	−0.031	0.196
Three years later	0.096	**0.684***	**−0.874****	0.101	−0.606*	0.768*	0.066	**0.697***	**−0.799****	**0.376**	**−0.094**	−0.390	0.357	0.485	−0.656*	0.707*	0.121	−0.613*
Areas	Lanzhou									Zhangye								
Correlation matrix	Woodland			Grassland			Urban land			Woodland			Grass land			Unused land		
Current year	**0.638***	**−0.646***	−0.149	**−0.541**	**0.481**	0.546	0.420	−0.453	0.081	0.113	−0.071	−0.266	**0.221**	**−0.239**	0.058	**−0.221**	**0.230**	−0.003
One year later	**0.472**	**−0.504**	0.044	**−0.384**	**0.401**	0.027	0.180	−0.212	0.161	0.333	−0.314	−0.199	**0.264**	**−0.288**	0.066	**−0.248**	**0.255**	0.033
Two years later	**0.181**	**−0.278**	0.690*	**−0.494**	**0.532**	−0.076	−0.118	0.041	0.697*	−0.183	0.124	0.376	**0.470**	**−0.430**	−0.330	**−0.424**	**0.378**	0.361
Three years later	**0.500**	**−0.494**	−0.325	**−0.195**	**0.229**	−0.246	0.567	−0.539	−0.500	0.388	−0.547	0.895**	−0.179	0.191	−0.093	0.060	−0.063	0.027
Correlation matrix	Jiuquan						Urumqi											
R	Grass land			Unused land			Woodland			Woodland			Grass land			Unused land		
Current year	**0.480**	**−0.580**	0.137	**−0.580**	**0.664***	−0.104	0.197	−0.197	–	**−0.626***	**0.626***	–	**0.648***	**−0.648***	–	−0.122	0.122	–
One year later	**0.593***	**−0.568**	−0.344	**−0.644***	**0.629***	0.341	0.118	−0.118	–	**−0.558**	**0.558**	–	**0.567**	**−0.567**	–	−0.086	0.086	–
Two years later	**0.728***	**−0.742***	−0.294	**−0.745***	**0.766***	0.251	0.116	−0.116	–	**−0.106**	**0.106**	–	**0.516**	**−0.516**	–	−0.364	0.364	–
Three years later	**0.280**	**−0.386**	0.387	**−0.329**	**0.430**	−0.341	−0.809**	0.809**	–	0.436	−0.436	–	−0.397	0.397	–	−0.622*	0.622*	–

*At 0.05 level (double side) significantly correlated; *at 0.01 level (double side) significantly correlated.

urban land in Zhengzhou). Grassland shows a low influence on particulate pollution in the current year (R=0.006, 0.094, 0.095) but an obvious influence in subsequent years (R=0.415, −0.852**, 0.596*) in Zhengzhou. The effects of LUCC on particulate pollution in the subsequent three years are relatively low according to the correlation between them. Woodland and grassland have a certain effect in the subsequent three years in Lanzhou. Grassland and unused land have a relatively smaller influence on particulate pollution, and the maximum influence appears two year later (R=0.470, −0.430, 0.330 for woodland and R=−0.424, 0.378, 0.361 for urban land) in Zhangye.

For two west-inland areas, Jiuquan and Urumqi, the change of grassland and unused land has an obvious influence on particulate pollution in the subsequent three years, and the most obvious influence in Jiuquan appears one or two years later. There is a gradual influence of LUCC on the particulate pollution in the subsequent three years. The correlation coefficients between the grassland and no pollution days are 0.480, 0.593*, and 0.728* and the unused land and no pollution days are −0.580, −0.644*, and −0.745* for the subsequent three years, respectively. The changes in grassland and unused land have the biggest influence on particulate pollution of the current year in Urumqi.

5. Conclusions

Particulate pollution and four types of main land use types were extracted in eight representative cities in China for the period off 2001–2010. The correlation between LUCC and particulate pollution was also calculated to explore and discuss the response of particulate pollution to LUCC in the three following aspects: the variation trend of particulate pollution with LUCC, the time-lag effect of LUCC on particulate pollution, and the dominant factor changes affecting urban air pollution. The following conclusions were obtained:

(1) The correlation between LUCC and particulate pollution is relatively low in Qingdao, which is clearly affected by the ocean. Urban land has a high correlation with particulate pollution in Jinan and Zhengzhou due to high-speed urban sprawl. Woodland shows obvious effects on the air quality in Xi'an and Lanzhou. Grassland and unused land are significantly related to particulate pollution in Jiuquan and Urumqi.
(2) LUCC has a small influence on current urban particulate pollution but shows an obvious time-lag effect in subsequent years. Urban land has a great influence in Jinan and Zhengzhou, and woodland has obvious effects on air quality in Zhengzhou, Xi'an, and Lanzhou in the subsequent three years. However, grassland and unused land exhibit an obvious influence on air quality in Zhangye, Jiuquan, and Urumqi with a strong time-lag effect.
(3) The dominant factor affecting particulate pollution gradually converts from ocean, to woodland, to urban land, and eventually into grassland and/or unused land, showing an obvious middle transition from the coast to inland areas. However, due to numerous dominant factors such as urban sprawl, grassland degradation, and deforestation, the response of particulate pollution to LUCC varies in different areas.

The results explained the correlation between atmospheric particulate matter distribution and different types of LUCC and provide a reference for regional development planning. However, the following problems still accompany this work. (1) Limited by the data and analysis methods, only several major surface types were selected to discuss the change and the correlation with the spatial distribution of particulate matter. In fact, there are many factors affecting the spatial distribution of atmospheric particulates, such as atmospheric circulation (winds) and sandstorms, which show a large correlation in addition to the regional spatial changes. (2) Because of the limitations of current remote sensing technology, certain error existed in the collected data. This error is also a factor that might affect the results of the correlation calculation. (3) Particulate pollution data used in this paper were obtained from the optical parameters of atmospheric particulate matter, not near-surface particulate matter, so the results might differ from our common knowledge.

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