Variations in dust contributions to air quality impairment in a temperate grassland of Inner Mongolia, China

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Abstract. Dust associated visibility impairment is the most noticeable air pollution phenomena, has important implications regarding air quality in developing cities. We integrated the commonly reported visibility with remote sensing, found that dust emission tended to decrease over Xilingol grassland. The temporal coherency between dust event and visibility reduction demonstrated dust was an important factor responsible for air quality impairment, but the differences in seasonal patterns and long-term trends among stations manifested some drops in visibility couldn't be solely attributed to dust activity. It is urgent to conclude the causes of visibility reduction in developing cities susceptible to dust impact in recent years.

1. Introduction

Visibility refers to the clarity or transparency of the atmosphere and the ability to see distant objects [1]. Global visibility had decreased substantially during 1973-2007 over land except in Europe [2]. Visibility reduction is one of the most noticeable effects of air pollution [3]. Visibility has been used as a surrogate of air quality [4]. Besides anthropogenic aerosols, sand and dust storms also contribute significantly to visibility reduction [5]. Before the advent of satellite remote sensing, visibility was the dominant variable used in mapping dust activity [6]. Visibility has been used as a substitute for aeolian dust source [6] and activity [7], because dust loading impairs visibility [8, 9]. In recent years, remote sensing has been proven to be very suitable for monitoring dust events. MODIS (Moderate Resolution Imaging Spectroradiometer) boarded on the Terra and Aqua satellites operated by the NASA (National Aeronautics and Space Administration) provides us with data on diurnal aerosol variations [10]. MODIS provides us with more detailed information on dust emission, transport and deposition [11-13].

Recent studies have been directed to visibility impairment in cities, and the contribution of aeolian dust as well [14]. As one of the most abundant aerosols in the atmosphere, dust has important implications regarding air quality [15]. In this study, we demonstrated the simultaneity of dust events and visibility reductions in 2000-2013 over a temperate grassland of Inner Mongolia, China, integrating satellite remote sensing with traditional visibility observations. The objective of the study was to clarify the contribution of aeolian dust to air quality impairment, to unveil other potential contributors, and to consider measures to improve air quality in the future development of cities.

2. Data and methods

2.1. Study area

Xilingol is located at the center of Inner Mongolia (figure 1), has high-quality natural pastures, used traditionally for nomadic farming. Rapid economic development and population growth since the 1980s increased the demand for agricultural production, resulting in higher stock densities and a shift in agricultural policy from nomadism to stationary farming in the late 1980s [16]. Xilingol has a continental climate, with a long, cold winter and a warm summer with little rain [17].

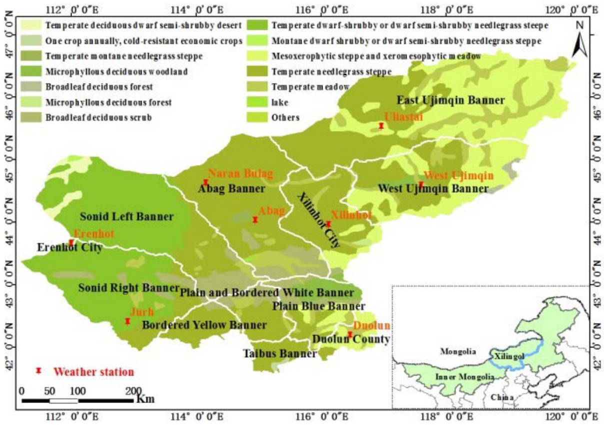


Figure 1. Landscape and observation station distribution in the study area.

2.2. Data and methods

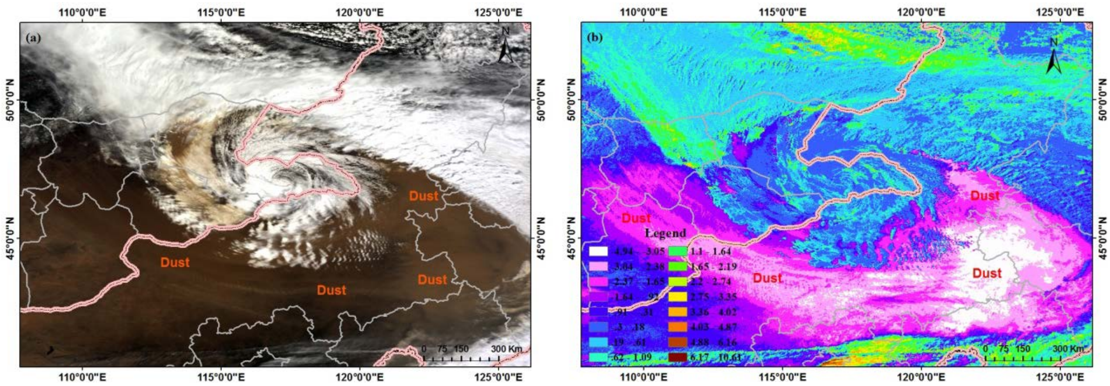


Figure 2. Dust identified by MODIS true-color composite image (a) and BTD (k) algorithm (b).

Daily mean visibility data were downloaded from NCDC (NOAA's National Climatic Data Center) climate data online. Data are available at eight weather stations in the study area (figure 1). In view of data availability, continuity and change of visibility specification in China [18], we analyzed visibility data in 2000-2013. MODIS L1B data from LAADS (the Level 1 and Atmosphere Archive and Distribution System) were used in this study. We analyzed 88 dust events observed from 2000 to 2013, including all the dust emitted from Xilingol Grassland [12, 13].

Dust can be identified using aerosol optical thickness algorithms [19], absorbing aerosol index [20], (thermal) infrared dust index [21] and other indices [22]. We compared dust discrimination methods [13], concluded that MODIS true color image (figure 2a) captured the emission and transport of dust, and that brightness temperature difference (BTD) (figure 2b) was the most consistently reliable technique for dust identification [13, 23]. Therefore, we used MODIS true color images and BTD algorithm to capture dust events. Contribution of dust to visibility impairment was measured by temporal consistency between satellite observed dust events and visibility reduction observations: (visibility reduction (days)/dust-induced visibility reduction (days)) × 100%.

3. Results

3.1. Dust event and visibility impairment: a case study

On May 11, 2011, MODIS captured dust blew out of the Gobi Desert and across the Mongolia-China border. The natural-color image presented that a counter-clockwise arc of dust swept across the border into China, then backed over the border into Mongolia. Clouds hovered over the dust plume, and some fringed the plume’s northern edge (figure 3a). This dust event significantly impaired visibility in Xilingol grassland (figure 3b). The visibility on May 11 decreased greatly to <15 km at eight synoptic weather stations, demonstrating the strength and influencing extent of the dust event. The temporal agreement verified the contribution of dust to mean daily visibility decline.

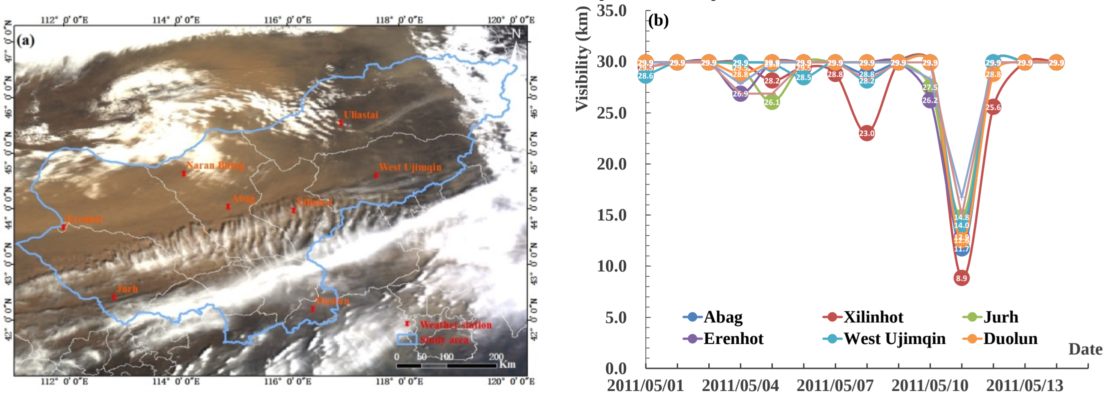


Figure 3. Dust event observed by MODIS on May 11, 2011 (a) and its impact on visibility (b).

3.2. Dust activities in 2000-2013

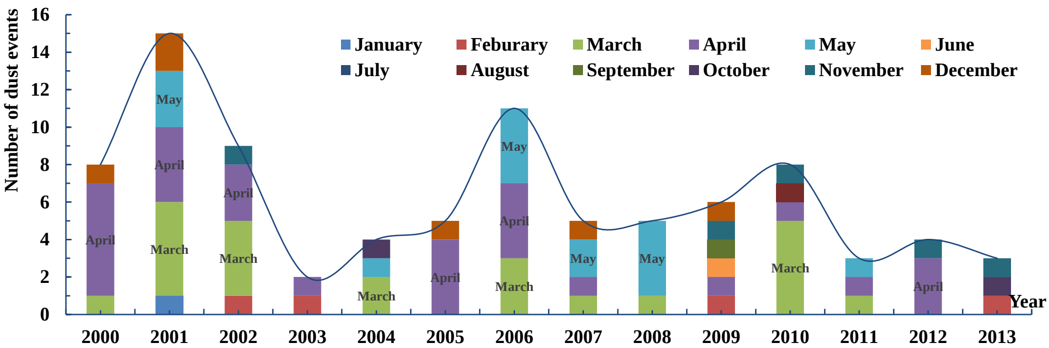
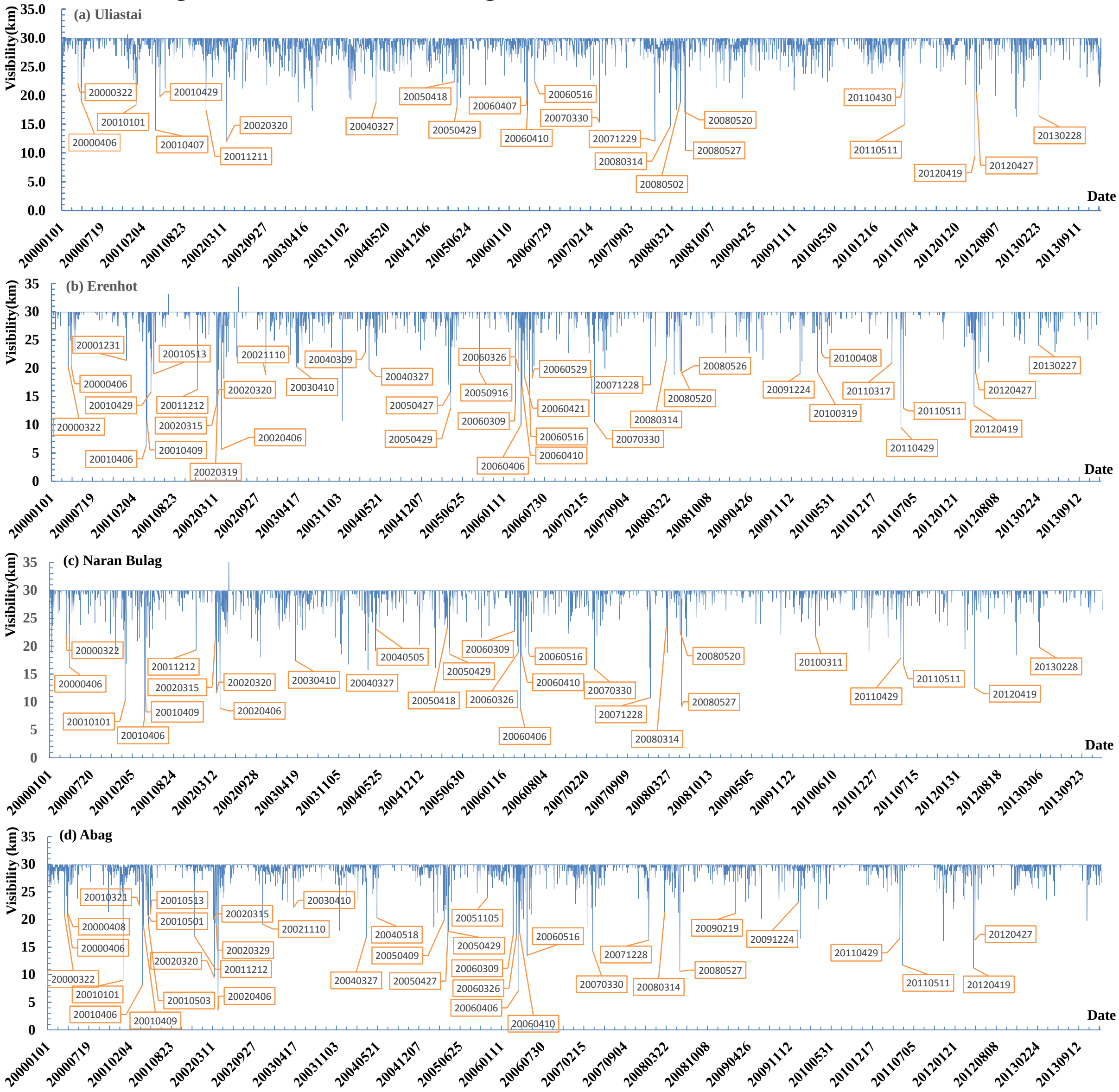


Figure 4. Dust events observed by MODIS in 2000-2013.

According to MODIS observations in 2000-2013, dust activities (figure 4) in Xilingol grassland were detected by analysing true colour and BTD images. Dust emissions changed much in the last 14 years. More dusty days occurred in 2000-2002 and 2004-2008, but fewer in 2003, and after 2010. About 75 percent dust events were observed during March to May.

3.3. Temporal and spatial coherency between dust events and visibility impairments in 2000-2013

Visibility impairments and their temporal associations with dust activities at eight stations over Xilingol grassland demonstrated the simultaneous occurrences of dust emission and visibility decline (figure 5). The dates of dust events captured by MODIS were coherent with the occurrences of visibility impairment. Concurrent with visibility impairment phenomena, dust events indicate its impacts on air quality. Visibility reduction demonstrated dust activity. Annual visibility reductions showed similar patterns to those of dust emissions at eight stations, verifying aeolian dust was an important factor leading to visibility impairment. Visibilities decreased in 2000-2002, 2005-2008, especially 2001-2002, 2006-2008, coincided with dustier spring in the study area. Seasonal visibility changes varied among stations, stations in the north (Uliastai (figure 5a), Erenhot (figure 5b), Naran Bulag (figure 5c), Abag (figure 5d) and West Ujimqin (figure 5f)) showed stronger annual change patterns than those in the south (Jurh (figure 5d), Xilinhot (figure 5g) and Duolun (figure 5h)). Besides seasonal patterns, differences among stations still included long-term trends. Jurh experienced more dusty days in 2000-2009; seven stations except Xilinhot city appeared to suffer less from visibility reductions in recent years, the frequencies of visibility impairments tended to be declining, especially at Jurh (figure 5e). In addition, some dust events associated visibility decreases were local phenomena, not all stations showing visibility declines; some were of great strength and extent, e. g., dust on May 27 2008 (figure 2), dust veiled the whole Xilingol grassland. Visibility impairment differed among stations, showing the differences in the strength and extent of dust events.



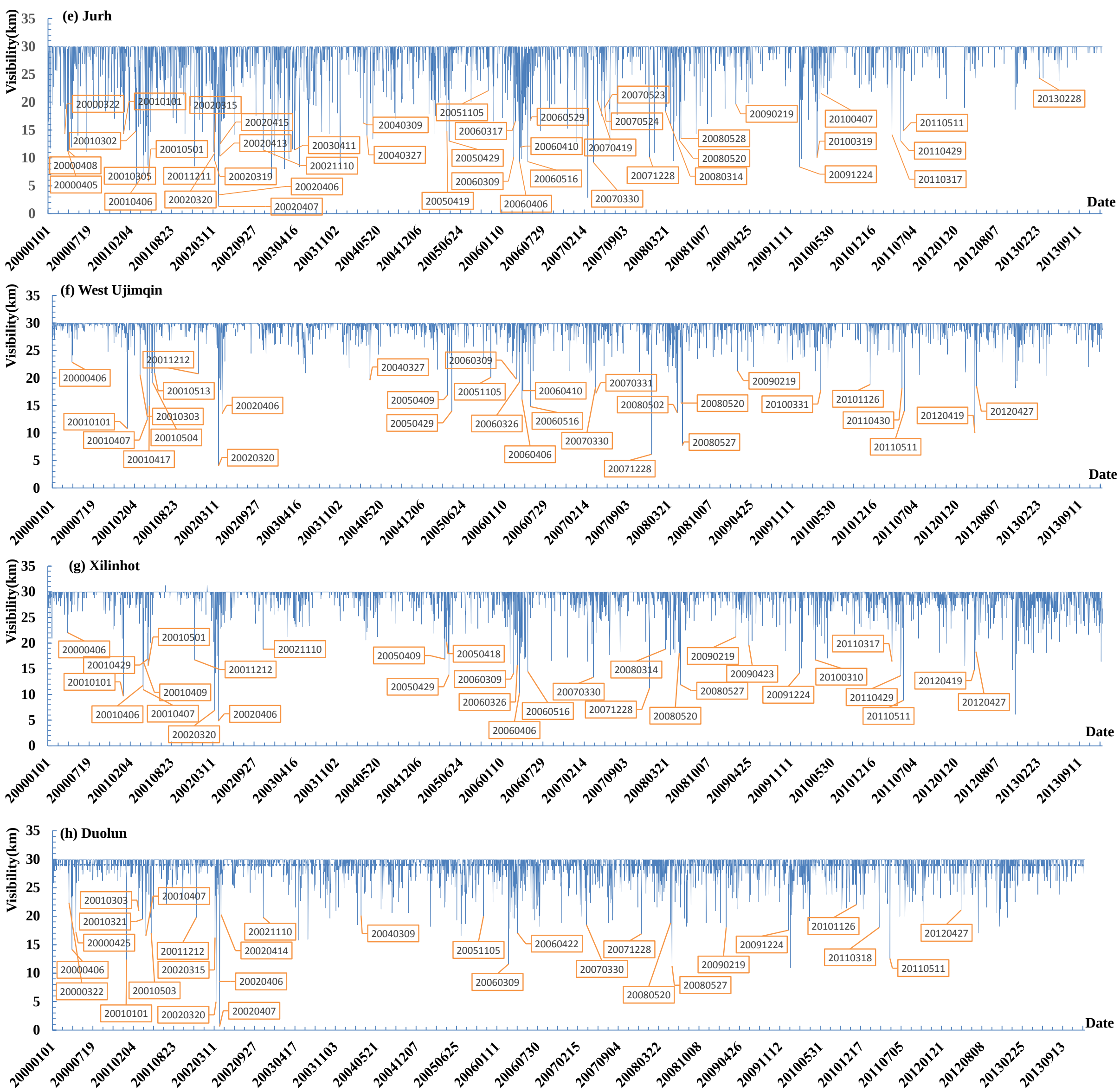


Figure 5. Visibility reductions and associated dust events in 2000-2013. Dates shown in the figures demonstrated the concurrences of dust events and visibility reductions.

3.4. Contributions of dust events to visibility impairments

Table 1. Number of visibility impairments (days) at different thresholds (km).

Station	<21	<20	<19	<18	<17	<16	<15	<14	<13	<12	<11	<10
Uliastai	43	36	27	20	12	10	8	4	4	3	2	1
Erenhot	49	42	30	22	20	17	14	13	9	8	8	5
Naran Bulag	49	43	30	20	18	12	10	10	9	7	6	4
Abag	46	37	30	24	18	12	12	11	9	9	7	6
Jurh	245	198	162	131	108	88	83	58	52	43	31	23
West Ujimqin	47	36	28	23	18	16	13	9	7	6	6	5
Xilinhot	94	71	63	47	37	26	21	15	12	12	9	7
Duolun	73	60	42	22	16	12	10	9	9	7	5	3

Table 2. Contributions (%) of dust events to visibility impairment at different thresholds (km).

Station	<21	<20	<19	<18	<17	<16	<15	<14	<13	<12	<11	<10
Uliastai	62.8	61.1	70.4	70.0	83.3	90.0	87.5	75.0	75.0	66.7	100.0	100.0
Erenhot	75.5	81.0	80.0	86.4	85.0	82.4	85.7	84.6	77.8	75.0	75.0	80.0
Naran Bulag	57.1	58.1	66.7	65.0	72.2	91.7	90.0	90.0	88.9	85.7	100.0	100.0
Abag	71.7	75.7	73.3	83.3	77.8	91.7	91.7	90.9	88.9	88.9	85.7	83.3
Jurh	43.3	46.0	49.4	52.7	56.5	56.8	57.8	58.6	59.6	65.1	64.5	69.6
West Ujimqin	72.3	80.6	85.7	95.7	94.4	93.8	92.3	88.9	85.7	83.3	83.3	80.0
Xilinhot	52.1	56.3	60.3	61.7	70.3	73.1	76.2	80.0	75.0	75.0	66.7	57.1
Duolun	52.1	55.0	57.1	72.7	68.8	58.3	70.0	66.7	66.7	57.1	40.0	66.7

In 2000-2013, the days of visibility below 21 km in Xilingol Grassland varied much, with the numbers at Jurh 2-5 times higher than those at other stations. Except Jurh, Xilinhot and Duolun, other five stations experienced similar low visibility days (figure 4, table 1). The contribution of dust activity to visibility impairment was measured by temporal consistency between MODIS captured dust events and observed visibility reduction phenomena (table 2). The contributions of dust to visibility reduction were different at eight stations, lower contributions were found at Jurh, Xilinhot and Duolun in Xilingol grassland.

4. Discussion and conclusions

Dust events significantly impaired visibility over Xilingol grassland. Dust emissions observed by MODIS tended to decrease over the time, as was proved by visibility records. Dust was more active in 2000-2002 and 2005-2009, these higher frequencies have been verified by earlier works [13].

The coherency demonstrated dust was an important factor leading to air quality impairment, but the differences in seasonal patterns and long-term trends among stations manifested that some drops in visibility could not be solely attributed to dust activity. Other factors might also be the contributors, such as meteorological variables [24], fog, haze [25], and others.

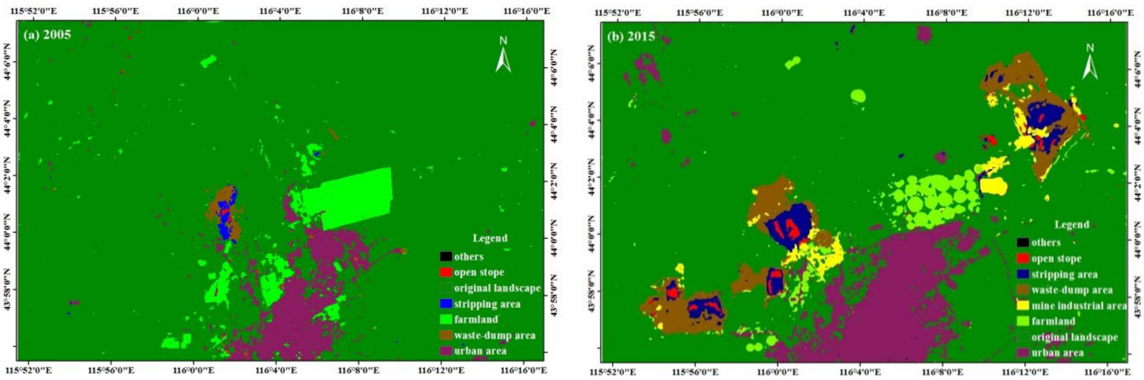


Figure 6. Land uses around Xilinhot in 2005 (a, Landsat 5 TM) and 2015 (b, Landsat 8 OLI).

Many publications discussed visibility changes in China [25, 26], but few gave its details in a temperate grassland. Taking Xilinhot as an example, supervised classification, with the support from GPS data, was used to divide land uses around Xilinhot into seven types (figure 6). The mining area increased in 2005-2015, e. g., waste-dump area grew by 3183.48 hm^2. With the growth of mining and urban areas, grassland decreased by 8661.15 hm^2. The markedly lower visibilities in Chinese megacities suggested that elevated aerosol loadings were responsible for the visibility degradation [26], due to the increased emission of pollutants from urbanization, economic and industrial developments [27]. Xilinhot ranked the second in days of low visibility, besides dust activity, mining and urbanization should also be important contributors to visibility reduction. Therefore, it is urgent to clarify the causes of visibility reduction in developing cities in China in recent years.

Acknowledgements
The authors gratefully acknowledge financial support from the National Natural Science Foundation of China (Grant Nos. 41261048 and 40961014).

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