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Mapping dustfall distribution in urban areas using remote sensing and ground spectral data

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HIGHLIGHTS

• A new method for dustfall mapping from satellite is proposed.
• MODIS satellite and ground based spectral data are integrated into the model.
• This method shows a good performance for dustfall detection in urban scale.

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ABSTRACT

The aim of this study was to utilize remote sensing and ground-based spectral data to assess dustfall distribution in urban areas. The ground-based spectral data denoted that dust has a significant impact on spectral features. Dusty leaves have an obviously lower reflectance than clean leaves in the near-infrared bands (780–1,300 nm). The correlation analysis between dustfall weight and spectral reflectance showed that spectroscopy in the 350–2,500-nm region produced useful dust information and could assist in dust weight estimation. A back propagation (BP) neutral network model was generated using spectral response functions and integrated remote sensing data to assess dustfall weight in the city of Beijing. Compared with actual dustfall weight, validation of the results showed a satisfactory accuracy with a lower root mean square error (RMSE) of 3.6 g/m^2. The derived dustfall distribution in Beijing indicated that dustfall was easily accumulated and increased in the south of the city. In addition, our results showed that construction sites and low-rise buildings with inappropriate land use were two main sources of dust pollution. This study offers a low-cost and effective method for investigating detailed dustfall in an urban environment. Environmental authorities may use this method for deriving dustfall distribution maps and pinpointing the sources of pollutants in urban areas.

1. Introduction

Dust diffusion and deposition are widely considered important factors affecting the ecological environment (Rashki et al., 2013). Airborne dust carrying heavy metals and particulate matter (PM) is recognized as the most harmful air component (Rai, 2013). Leaf dustfall can also impair plant growth, and a significant negative correlation was found between dust and pigment content (Prusty et al., 2005). Thus, determining the spatial distribution of dust and analyzing its sources can provide a data basis for environmental management agencies to mitigate air pollution.

However, some studies that measured atmospheric pollution by sampling particulates were expensive and time consuming (Shu et al., 2000; Likuku et al., 2013), and others required a high density of sampling points to ensure accuracy, which wasted labor and resulted in poor simultaneity (Chudnovsky and Ben-Dor, 2008). Although satellite-based solutions, which can solve problems mentioned above, have been widely applied to monitor air pollution, there are still many problems associated with this technique, such as a poor relationship between selected indices (aerosol optical thickness (AOT), etc.) and air quality (Bilal et al., 2014; Soni et al., 2014; Rahimi et al., 2014). In addition, many studies used satellite images to obtain AOT and explored its relationship with PM (Chu et al., 2003; Gupta et al., 2006; Wong et al., 2011; Luo et al., 2014). However, few researchers have applied satellite images to monitor urban dust and focused on the characteristics and source of the dustfall (Lue et al., 2010).

Recent studies revealed that dust deposited on leaf surfaces may be used as an indicator of air pollution (Yang et al., 2011; Ram et al., 2014). By collecting particulates accumulated on pine needles, Urbat et al. (2004) found that the main source of air pollution in Cologne was motor vehicles. Plant cover in urban areas could be used to acquire the

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spatial distribution of atmospheric dust (Lu et al., 2008; Luo et al., 2013; Peng et al., 2013). Yan et al. (2014a) used the near-infrared band to estimate the amount of leaf dust deposition, and the results showed good accuracy. Chudnovsky et al. (2007) developed a new spectral-based method for estimating indoor settled dust weight. Ong et al. (2001) used visible, near-infrared, and short-wave-infrared high-resolution spectral images to quantify the leaf dust load of mangroves. Thus, remote sensing can be used to investigate dust pollution in urban areas (Zheng et al., 2001).

The purpose of this work was to establish a reliable method for monitoring dust distribution with the aid of satellite images and plant leaf spectral data. We first analyzed the correlation between spectral reflectance and dust on plants. Based on this correlation, dust distribution was obtained using a neutral network model. Finally, the sources of dust in urban areas were discussed.

2. Materials and methods

2.1. Study area

This study was conducted in the city of Beijing, which lies at east longitude 39.92° and north latitude 116.46° and covers an area of 16,807 km^2. It is located at the northern edge of the North China Plain at the junction of the Inner Mongolia Plateau, the Loess Plateau, and the North China Plain. The city's elevation decreases gradually from west to east due to the distribution of mountains and plain. The climate in Beijing is typical sub-humid warm temperature continental monsoon, with annual average temperatures between 10 °C and 12 °C and rainfall of 626 mm (Hou et al., 2012).

With the development of the city capital construction, the land cover in Beijing has changed markedly. Many main roads and residential buildings have been built to accommodate the increase in population and the consequent increase in the number of motor vehicles. Even though the Beijing city government has made great efforts to improve the environment, urban air pollution problems have become increasingly serious.

2.2. Satellite data

Moderate resolution Imaging Spectroradiometer (MODIS) Terra L1B data were obtained from NASA's Goddard Space Flight Center (http://modis.gsfc.nasa.gov). The MODIS L1B data contains calibrated and geolocated at-aperture radiances for 36 bands generated from MODIS Level 1A sensor counts (Bilal et al., 2013). This study used MODIS images acquired on July 2, August 3, and September 25 2013. Table 1 lists the weather information from the days when MODIS overpassed.

2.3. Plants collection

In this study, *Euonymus japonica* L., *Sophora japonica* L., and *Populustomentosa* L. Carr. were selected as experimental plants. *Euonymus japonica* L. is one of the main shrub species in Beijing, while *Sophora japonica* L. and *Populustomentosa* L. Carr. are also common in this area (Yang et al., 2005; Yan et al., 2014b). The above plants have been widely used for landscaping around cities. Experimental leaf samples were collected from 44 sampling locations around Beijing, and their spatial distributions are shown in Fig. 1.

Table 1
Weather information during a moderate resolution imaging spectroradiometer (MODIS) overpass.

Date	Wind direction (°)	Wind speed (m/s)	Relative humidity (%)	AOT at 550 nm
7/2/2013	290	5	49	0.11
8/3/2013	130	2	43	0.25
9/25/2013	290	4	18	0.06

2.4. Spectral measurements and processing

Initially, each plant leaf was weighed using an electronic analytic balance (1/10,000 g scale). Then, the spectral reflectances of the leaves were measured using a spectrometer (Analytical Spectral Devices FieldSpec Pro, ASD 2008) equipped with a Plant Probe (ASD auxiliary product, Halogen bulb light source type) and an ASD Leaf Clip. The ASD is a single-beam field spectroradiometer covering a range of 350–2,500 nm with a total of 2,100 spectral bands. The spectral measurements were repeated 10 times for each sample, and the mean value was taken to represent each leaf's spectral reflectance (Hansena and Schjoerring, 2003; Haboudane et al., 2004). Subsequently, leaves were cleaned with ultra-pure water and dried by absorbent paper. The cleaned leaves were reweighed, and the reflectances were measured again. Although leaf reflectance is affected by many factors, such as chlorophyll, plant health, and water content, this research compared reflectance data between dust and clean leaves, which was referred to as a samples' self-comparison and, thus, neglected possible interfering factors.

Another issue was that, due to low spatial resolution of MODIS images and the limited study area, urban cities always contained mixed pixels, which made dustfall retrieval inaccurate. Thus, when collecting leaf samples, the selected locations needed to be widely covered by vegetation cover. In addition, in order to eliminate the interference of plant type on the retrieval result, mean spectral values for three plants at single site were calculated and used for final dustfall weight calculations.

In order to transfer ground-measured data to satellite images, a leaf's narrow-band spectra was resampled at broad-band according to the relative spectral response function of MODIS (Supplementary Fig. 1). The MODIS spectral response function is as follows (Ghulam et al., 2008):

$$R_{\mathrm{MODIS}}(\lambda) = \frac{\int_{\lambda_{\min}}^{\lambda_{\max}} R_{\mathrm{Leaf}}(\lambda)\,\mathrm{f}(\lambda)d\lambda}{\int_{\lambda_{\min}}^{\lambda_{\max}} \mathrm{f}(\lambda)d\lambda} \tag{1}$$

where $R_{\mathrm{MODIS}}(\lambda)$ refers to broad-band reflectance, $f(\lambda)$ refers to the MODIS spectral response function at a corresponding waveband, $\lambda_{\min}$ and $\lambda_{\max}$ refer to the lower and upper limit of band internal, and λ indicates the center wavelength (nm) in each band. Then, the ratio of the reflectance between dust and clean leaves was calculated by the following:

$$r(\lambda) = \frac{R_{\mathrm{MODIS}}^{\mathrm{Dust}}(\lambda)}{R_{\mathrm{MODIS}}^{\mathrm{Clean}}(\lambda)} \tag{2}$$

where $R_{\mathrm{MODIS}}^{\mathrm{Dust}}(\lambda)$ and $R_{\mathrm{MODIS}}^{\mathrm{Clean}}(\lambda)$ are dust and clean leaf's reflectance corresponding to a specific band of MODIS.

2.5. Dustfall retrieval

The central idea of this retrieval method is to find out the relationship between spectral reflectance and dustfall weight and to sequentially use “dust” images and “clean” images as input parameters to calculate the whole dust distribution. Plant leaves can be cleaned by heavy continuous rain (Przybysz et al., 2014). Thus, based on Table 2, MODIS images from July 2 2013 were considered “clean” images, and images from August 3 and September 25 2013 were considered “dust” images.

The back propagation (BP) neutral network model is considered a generalization of the delta rule for nonlinear activation functions and has been successfully applied in many environmental studies (Tumbo et al., 2002; Pal et al., 2003; Sahin, 2012; Valipour et al., 2012, 2013).