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Atmospheric removal of $PM_{2.5}$ by man-made Three Northern Regions Shelter Forest in Northern China estimated using satellite retrieved $PM_{2.5}$ concentration

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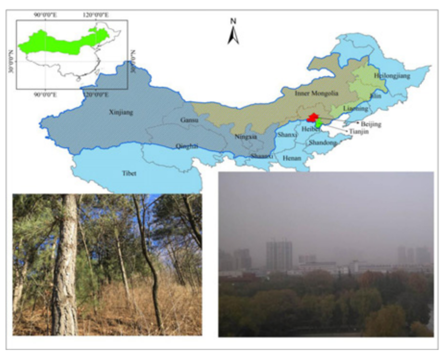
HIGHLIGHTS

- An inferential method combining $PM_{2.5}$ concentration and modeled deposition velocity was used to estimate $PM_{2.5}$ flux
- The Green Great Wall in China makes a moderate contribution to $PM_{2.5}$ atmospheric removal
- Increasing deposition fluxes of $PM_{2.5}$ are more evident in Central-North China due to increasing vegetation coverage
- Contribution of the TNRSF to the $PM_{2.5}$ removal in 2010 increased 30% compared to 1980

GRAPHICAL ABSTRACT



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ABSTRACT

Atmospheric removal of $PM_{2.5}$ by the Three Northern Regions Shelter Forest (TNRSF) – the so called Green Great Wall (GGW) in northern China through dry deposition process was estimated using a bulk big-leaf model and a vegetation collection model. Decadal trend of $PM_{2.5}$ dry deposition flux from 1999 to 2010 was calculated from modeled dry deposition velocity and air concentration retrieved from the satellite remote sensing. Dry deposition velocities of $PM_{2.5}$ calculated using the two deposition models increased in many places of the TNRSF over the last decade due to increasing vegetation coverage of the TNRSF. Both increasing deposition velocity due to forest expansion and $PM_{2.5}$ atmospheric level contributed to the increasing deposition flux of $PM_{2.5}$. The highest atmospheric deposition flux of $PM_{2.5}$ was found in the Central-north region covering Beijing-Tianjin-Hebei area, followed by the Northwestern and the Northeastern regions of the TNRSF. While greater collection of $PM_{2.5}$ by vegetation was identified in the Northeastern region of the TNRSF due to higher forest coverage over this region, the most significant incline of the $PM_{2.5}$ atmospheric removal due to vegetation collection was discerned in the Central-north region because of the most rapid increase in the vegetation coverage in this region. A total mass of 2.85×10^7 t $PM_{2.5}$ was estimated to be removed from the atmosphere through dry deposition process over the TNRSF from 1999 to 2010. The two deposition models simulated similar magnitude and spatial patterns of $PM_{2.5}$ dry deposition fluxes. Our results suggest that the TNRSF plays a moderate role in $PM_{2.5}$ uptake, but enhances $PM_{2.5}$ atmospheric removal by 30% in 2010 than in 1980.

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1. Introduction

Rapid industrialization and urbanization in China have posed serious air pollution challenges in many places of the country. Fine particulate matter, or $PM_{2.5}$ (aerodynamic diameter < 2.5 μm) is one of the major air pollutants due to its adverse health effects causing increasing mortality and morbidity rates (Samet et al., 2000; Pinkerton et al., 2000; Wang et al., 2013; Kim et al., 2015; Feng et al., 2016). $PM_{2.5}$ is a carrier of toxic chemicals including heavy metals and polycyclic aromatic hydrocarbons (PAHs) (Liacos et al., 2012; Pandey et al., 2013; Pandey et al., 2011), causing health risks of human beings (Dejmek et al., 2000; Pope et al., 2002; Dockery and Stone, 2007; Liacos et al., 2012).

Suspended particles can be removed from the atmosphere by precipitation (wet deposition) and by underlying surfaces through a dry deposition process. Although the dry deposition process is a slower process than wet deposition, it occurs all times as compared to highly episodic wet deposition (Zhang and Vet, 2006). Dry deposition of atmospheric particles is a combination of different mechanical processes, including Brownian diffusion, interception, inertial impaction, and sedimentation (Petroff et al., 2008; Zhang et al., 2001; Schaubroeck et al., 2014). The large surface areas of leaves, trunks, twigs and fruits, and large roughness lengths over the vegetation surfaces can result in more efficient capture of aerosols and other pollutants than other land surfaces (Beckett et al., 1998; Hill, 1971; Janhäll, 2015). It was estimated that 7.1×10^5 metric tons of air pollutants (O_3, PM_{10}, NO_2, SO_2, CO) were removed annually by urban trees in the United States (U.S.), equivalent to an economic value of $3.8 billion in 1994 (Nowak et al., 2006). Nowak et al. (2013) also investigated the effects of trees on $PM_{2.5}$ concentrations and human health in 10 cities of the U.S. They reported that annual $PM_{2.5}$ removal by trees in each city ranged from 4.7 tons (Syracuse) to 64.5 tons (Atlanta), and mortality reduction was typically 1 person yr^{-1} due to reduced $PM_{2.5}$ through tree uptake. The most significant mortality reduction was estimated in New York City at 7.6 people yr^{-1}. Likewise, it has been reported that 451 t $PM_{2.5}$ was removed by trees planted in the Beijing Plain in 2012 (Chen et al., 2014).

Most previous studies on dry deposition are chemically resolved, i.e., focusing on certain groups of chemical pollutants. In the present study, however, the bulk $PM_{2.5}$ dry deposition is investigated from the following considerations: (1) $PM_{2.5}$ has become the most serious pollutant across China, and knowledge in the impact of changing land-use on its removal and thus air concentration level is important for making emission control policies; (2) while chemically-resolved $PM_{2.5}$ data are not available on the national scale, bulk $PM_{2.5}$ concentration data can be roughly estimated from satellite aerosols optical depth (AOD) measurements; and (3) if $PM_{2.5}$ dry deposition flux is firstly estimated, flux of any aerosol chemical species can be roughly estimated from local to regional scales as long as the mass fraction of the chemical species in $PM_{2.5}$ is known. Previous studies on PM dry deposition in China were very limited and mostly focused on local scales (e.g., Liu et al., 2016).

The TNRSF accounts for 42.4% of the total land area in mainland China (Fig. S1). Recently, the atmospheric removal of SO_2 (sulfur dioxide), NO_x (nitrogen dioxide), and polycyclic aromatic hydrocarbons (PAHs), as well as the release of isoprene in the TNRSF have been assessed (Zhang et al., 2015, 2016; Huang et al., 2016). The present study aims to elucidate and quantify the impact of the TNRSF on the atmospheric removal of fine particles in northern China. It is noted that the dry removal process is directly affected by underlying surfaces, wet removal process has no direct link with underlying surfaces but is controlled by in- and below-cloud scavenging of pollutants. However, precipitation can enhance dry removal over forest canopies through washing off previously intercepted particles by canopies and reduce particle suspension (Nowak et al., 2013; Schaubroeck et al., 2014). It is also worthwhile to point out that the dry deposition flux estimated in the present study does not take into account the effects of particle resuspension and net deposition. The results likely represent the upper-end estimation of net dry removal of particles. Knowledge gained in this study is expected to fill critical knowledge gaps in understanding air quality issues in northern China subject to the increasing vegetation coverage in the TNRSF. Awareness of the implications of this large scale artificial forest to air quality is important for assessing impacts and benefits of the TNRSF program.

2. Methodology

2.1. Flux models

Inferential method was used in the present study to estimate the dry deposition flux of $PM_{2.5}$ (Zhang et al., 2005; Nowlan et al., 2014; Zhang et al., 2015). Two dry deposition models including a bulk big-leaf model (Zhang and He, 2014) and a vegetation collection model (Petroff et al., 2008) were employed. Dry deposition flux of $PM_{2.5}$ (f, mg m^{-2} h^{-1}) was calculated as a product of the satellite-retrieved $PM_{2.5}$ air concentration (C, μg m^{-3}) and model-calculated dry deposition velocity (V_d, m s^{-1}). Note that the terms of dry deposition and dry removal are both used interchangeably below.

2.1.1. The bulk big-leaf model

The bulk dry deposition model for atmospheric particles (Zhang and He, 2014) was used here to estimate gridded V_d over the TNRSF region with some modification of input parameters. This model uses an empirical algorithm to calculate bulk V_d for fine ($PM_{2.5}$), coarse ($PM_{2.5-10}$), and giant (particles having a diameter > 10 μm) atmospheric particles. In this model, V_d is estimated subject to land use type (LUC), leaf area index (LAI), surface roughness length (Z_0), and meteorological conditions. Twenty-six land use types were used in the model, which were identified using LAI and Z_0 estimated from satellite remote sensing data (Zhang et al., 2015, 2016). Only V_d of $PM_{2.5}$ is needed in this study, which is calculated as:

$$V_d(PM_{2.5}) = V_g(PM_{2.5}) + 1/(R_a + 1/(a_1 u^*)), \quad (1)$$

where $V_d(PM_{2.5})$ is the dry deposition velocity of $PM_{2.5}$ (m s^{-1}), $V_g(PM_{2.5})$ is the gravitational settling velocity which depends strongly on particle size and slightly on particle density and meteorological conditions, but not on land use (LUC). Thus, a constant V_g can be used for a fixed particle size distribution, which is set as 3.7×10^{-5} m s^{-1} in this study. a_1 is the LUC–dependent empirical constant given by the model. In the model, the original 26 LUCs were regrouped into five LUC groups (Zhang and He, 2014), each with a constant a_1. The different removal efficiencies by different tree types (specified as different land use) are reflected in the land-use dependent empirical constants used in the model. R_a is the aerodynamic resistance and u_* is the friction velocity (m s^{-1}). Both R_a and u_* depend on meteorological conditions (winds, temperature) and change with underlying surfaces characterized by LAI and Z_0 values. The model was set up over the TNRSF with a grid spacing of 0.25° × 0.25° latitude/longitude to produce gridded V_d of $PM_{2.5}$. Dry deposition flux (f, mg m^{-2} h^{-1}) is calculated as a product of the satellite retrieved $PM_{2.5}$ air concentration (C, μg m^{-3}) and V_d (Eq. (1)):

$$f = V_d C \quad (2)$$

2.1.2. The vegetation collection model

Over an underlying surface covered by vegetation, particle collection by vegetation refers to the interaction between vegetation and the particles (Petroff et al., 2008). Vegetation collection is a part of the dry deposition process which represents most fractions of dry deposition fluxes except for soil uptake. Particle collection can be quantified by the collection rate which accounts for the particles captured by vegetation in a canopy volume unit (Petroff et al., 2008). The collection rate for