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Invited paper

Trends of deposition fluxes and loadings of sulfur dioxide and nitrogen oxides in the artificial Three Northern Regions Shelter Forest across northern China

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ABSTRACT

This study provides the first estimate of dry deposition fluxes of criteria air pollutants (SO_2 and NO_x) across the Three Northern Regions Shelter Forest (TNRSF) region in Northern China and their long-term trends from 1982 to 2010 using the inferential method. Dry deposition velocities of SO_2 and NO_x increased in many places of the TNRSF up to 118.2% for SO_2 and 112.1% for NO_x over the last three decades due to the increased vegetation coverage over the TNRSF. The highest atmospheric deposition fluxes of SO_2 and NO_x were found in the Central-North China region, followed by the Northeast and the Northwest China regions of the TNRSF. A total of 820,000 t SO_2 and 218,000 t NO_x was estimated to be removed from the atmosphere through dry deposition process over the TNRSF from 1982 to 2010. About 50% of the total removal occurred in the Central-North China region. The estimated total SO_2 and NO_x dry deposition fluxes from 1982 to 2010 between a TNRSF site in this region and an adjacent farmland outside the TNRSF showed that the fluxes of these two chemicals at the TNRSF site were the factors of 2–3 greater than their fluxes in the farmland.

1. Introduction

As the largest afforestation activity in human history, the Three Northern Regions Shelter Forest (TNRSF) in northern China has improved significantly the local ecological environment and climate. The TNRSF program, also known as'the Great Green Wall', began in 1978, with proposed end result of increasing Northern China's forest coverage from 5% to 15% by 2050. The program is the largest ecological reforestation program in the world in human history. The TNRSF covers 551 counties of 13 provinces in Northern China, extending from 73°26′E to 127°50′E, and from 33°30′N to 50°12′N (Fig. 1), and covering an area of 4.069×10^6 km^2 which accounts for 42.4% of the total area in mainland China. By the end of the fourth phase (2001–2010) of the TNRSF program, the vegetation coverage over the three northern regions (Northwest, Central-North, and Northeast, Fig. 1 caption) in China has increased from 5% to 12.4% and reached 2.647×10^8 ha (Wang et al., 2011; Central Government of China, 2012). The construction of the TNRSF aims to slow down desertification, prevent the loss of water and soil from land erosion, and improve ecological environment in Northern China. Since the launch of the program, the TNRSF has been playing an increasing role in mitigating local ecological environment and climate (Pang, 1992; Cheng and Gu, 1992; Parungo et al., 1994; Hu et al., 2001; Zhong et al., 2001; Ding et al., 2005; Liu et al., 2008; Yan et al., 2011; Zheng and Zhu, 2013). Increasing forest biomass carbon storage across China has also been largely attributed to artificial afforestation (Fang et al., 2001; Tan et al., 2007; Zhang et al., 2013). However, the influence of the TNRSF on air pollutants fates has not been paid much attention.

Since the early 1980s, rapid industrialization and urbanization have been imposing serious adverse effects on air quality, and posing increasing threat to human health and environment across China, particularly in Northern China where most heavy industries in China are located. The coal combustion generated emissions of air pollutants, such as sulfur dioxide (SO_2) and particulate matter, have increased in parallel with the increase of the forest coverage

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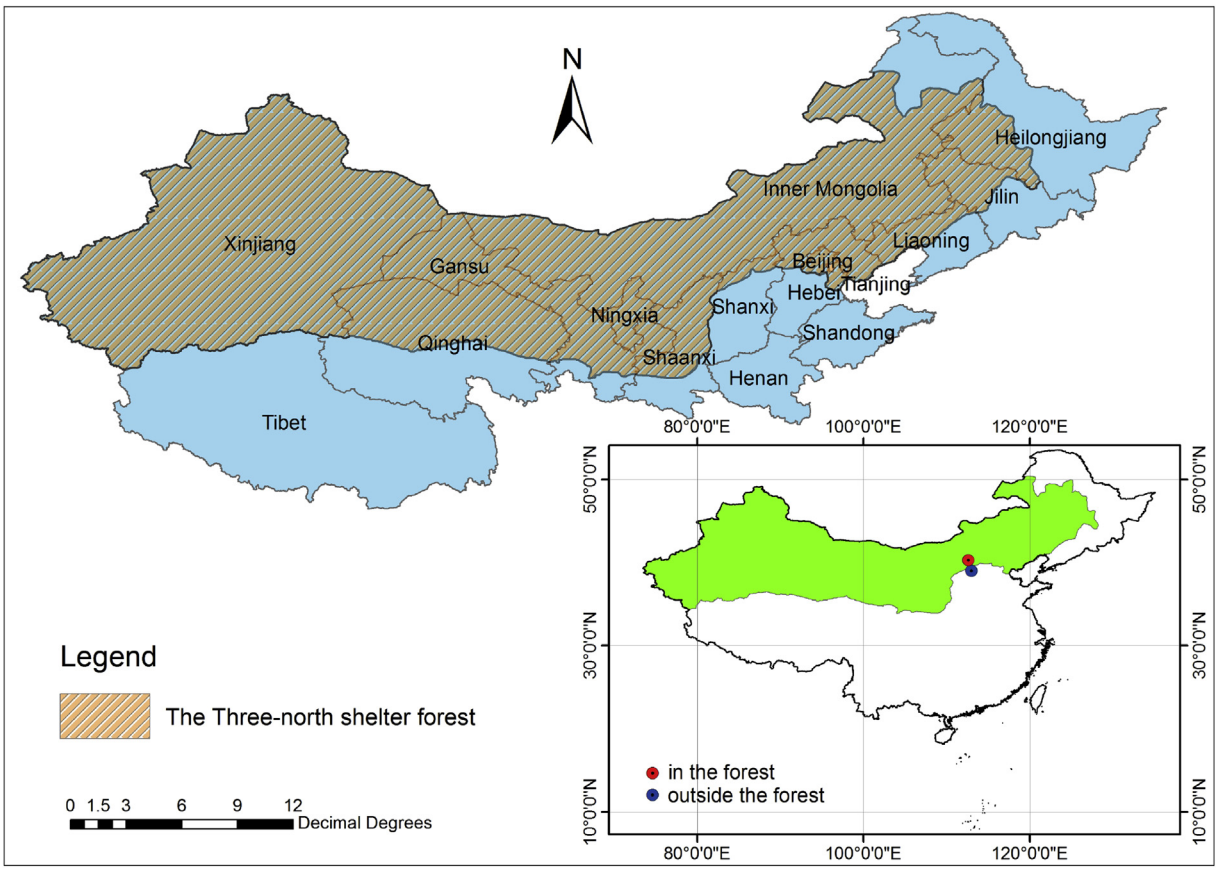

Fig. 1. The Three Northern Regions Shelter Forest (TNRSF) in Northern China. The Northwest China region of the TNRSF includes Xinjiang, Gansu, the north of Qinghai, Ningxia, West Inner Mongolia, and the north of Shaanxi; The Central-north China region includes the north of Shanxi and Hebei provinces, Beijing, Tianjin, and Central Inner Mongolia; The Northeast China region includes East Inner Mongolia, part of Liaoning, Jilin, and Heilongjiang provinces. Red and blue circles in the inner figure (right-lower corner of Fig. 1) indicate locations in and outside the TNRSF from which dry deposition fluxes of SO_2 and NO_x are extracted for comparison (see Results and Discussions section). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

by the TNRSF program since the early 1980s. It has been widely known that plants can uptake air pollutants, and natural and artificial vegetation can be regarded as a 'sink' for atmospheric pollutants in terrestrial ecosystems and cities (Rogers et al., 2012; Scott et al., 1998; Morikawa et al., 1998; Nowak et al., 2006, 2014; Hogberg, 2007; Myles et al., 2012; Camporn, 2013; Fenn et al., 2013; Adon et al., 2013, 2010). Pollutants removal from the atmosphere by vegetation and other underlying surfaces (soil, water, snow, ice) has implications on air quality, climate and ecosystem health since this process controls pollutants lifetimes in air and their inputs to ecosystems, and has been addressed in literature through the definition of dry deposition (Wesely and Hicks, 2000).

The TNRSF covers almost the entire Northern China and enlarges significantly the forest coverage in this region during the last three decades. Assessing how this program affects air pollutants fates in Northern China can provide scientific basis for establishing future pollutant emission control policies and insight into understanding of the interactions between human activities and environment. Quantifying atmospheric deposition of key pollutants, such as sulfur and nitrogen species, is needed to assess air quality and ecosystem related issues imposed by these pollutants (Fowler et al., 2009). Ideally, dry and wet deposition of major sulphur and nitrogen species should all be estimated together to generate a complete picture (Vet et al., 2014). Due to the lack of concentration data, the present study first focused only on two pollutant species, SO_2 and NO_x (=NO + NO_2) and only on dry deposition estimation. In fact, a recent study by Nowlan et al. (2014) has provided an estimation of the global SO_2 and NO_2 dry deposition fluxes at the spatial resolution of 0.1° × 0.1° using satellite remote sensing pollutants concentrations. It should be noted that satellite data can only be used for inferring column concentration and additional assumptions need to be made to generate surface concentration data. The latter is needed in the estimation of dry deposition. The present study provides an alternative estimation using emission data for inferring surface concentration, although only focused on the region of North China.

A framework of estimating dry deposition over North China is firstly developed in this study. The spatial pattern of the dry deposition of SO_2 and NO_2 in North China and their long-term trends associated with the expansion of the TNRSF from 1982 to 2010 are then investigated. Total loadings of SO_2 and NO_x to the TNRSF are also estimated to elucidate the proportion of the SO_2 and NO_x emissions removed from the atmosphere by the aggrading forest. The present study does not aim to determine seasonal and annual patterns of deposition fluxes of SO_2 and NO_x, instead, long-term trend is investigated to assess the potential influence of the development and expansion of the TNRSF on air pollutants uptake.

2. Methodology

2.1. Estimation of SO_2 and NO_x air concentrations from emission inventories

Most air monitoring programs for criteria air pollutants in China were undertaken in urban areas or near major point sources. There were almost no ambient measurement data of SO_2 and NO_x