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Invited paper

Identification of sources of polycyclic aromatic hydrocarbons based on concentrations in soils from two sides of the Himalayas between China and Nepal☆

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ABSTRACT

To understand distribution and sources of polycyclic aromatic hydrocarbons (PAHs) in the Himalayas, 77 soil samples were collected from the northern side of the Himalayas, China (NSHC), and the southern side of the Himalayas, Nepal (SSHN), based on altitude, land use and possible trans-boundary transport of PAHs driven by wind from Nepal to the Tibetan Plateau, China. Soils from the SSHN had mean PAH concentration greater than those from the NSHC. Greater concentrations of PAHs in soils were mainly distributed near main roads and agricultural and urban areas. PAHs with 2–3 rings were the most abundant PAHs in the soils from the Himalayas. Concentrations of volatile PAHs were significantly and positively correlated with altitude. Simulations of trajectories of air masses indicated that distributions of soil PAH concentrations were associated with the cyclic patterns of the monsoon. PAH emissions from traffic and combustion of biomass or coal greatly contributed to concentrations of PAHs in soils from the Himalayas.

1. Introduction

Due to atmospheric and temperature gradients, distributions of polycyclic aromatic hydrocarbons (PAHs) are dependent on the altitude. This phenomenon has been described as the "altitude effect". The transport of PAHs to remote areas and their fates have received increasing attention in the last decade (Wania and Mackay, 1996). Long-Range Atmospheric Transport (LRAT) is driven by wind, deposition and air–soil exchange, which are the most important global transport pathways for PAHs and the most important processes governing their global distribution.

High mountains are similar to the Arctic in terms of their lower temperatures, ice cover, remoteness, and ecological community structures that vary along altitudinal gradients. PAH distributions change along altitudinal gradients in these regions and are governed by the relative proximity to emission sources, local meteorological conditions and ecological gradients (Tremolada et al., 2008). The Himalayas have large variations in altitude, including Mt. Everest, which is the highest mountain in the world with an altitude of 8848 m. The Tibetan Plateau, China (TPC) is on northern side of the Himalayas and is referred to as the "Roof of the World" or the "Earth's Third Pole". The Himalayas have a cold and harsh climate, and they might act as cold traps for airborne semi-volatile

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contaminants such as PAHs (Dachs et al., 1999). Meanwhile, due to the comparatively small human population, the Himalayas are remote from modern industrial and commercial activities (Loewen et al., 2005). Therefore, the Himalayas are regarded as an ideal site for studying regional and global atmospheric circulation of PAHs (Wang et al., 2014). However, despite the unique geography and climate of the Himalayas, emissions of PAHs from adjacent countries such as Nepal and India are estimated to be much greater than those within the TPC, which potentially has an influence on the environment and ecosystems of the Himalayas and even the TPC (Zhang and Tao, 2009).

In recent years, the LRAT of PAHs has been studied in remote mountainous regions (Elliott et al., 2012; Aichner et al., 2007). The main source of PAHs in the mountains is deposition from the atmosphere (Wang et al., 2007). Soil plays an important role in the global fate and distribution of PAHs. Due to its large capacity to retain hydrophobic compounds, it has been identified as an effective reservoir/sink of PAHs in terrestrial environments (Bhatt and Sachan, 2004; Wang et al., 2014). Furthermore, it has to be regarded as a long-term archive of the atmospheric deposition rather than an indicator of the actual inputs. Studies of the Himalayas have indicated that PAHs emitted in Nepal and India may be transported by the Southern Asian monsoon along valleys from the Indian Subcontinent to the Himalayas (Kang et al., 2009). It has been reported that concentrations of PAHs in soils of Nepal (184–10,279 ng/g, dry weight (dw)) (Aichner et al., 2007) were greater than those reported in northern slope of the Central-Himalayas on the TPC (5.5–62.2 ng/g, dw) (Wang et al., 2014). The concentration of PAHs in soils might pose risks to the ecosystem of the Himalayas, which is also an important source of freshwater for as much as one sixth of the world's population (including China, India and Nepal) (Loewen et al., 2005). Therefore, it is important not only to know the spatial distribution of the concentrations, pathways (sources), and potential health effects of PAHs in the soils on both sides of the Himalayas between China and Nepal but also to understand the cross-border migration and spatial variability of atmospheric deposition of PAHs between South Asia and the most pristine and remote areas of the TPC. However, so far, no large-scale investigation of concentrations of PAHs in soils from both sides of the Himalayas between China and Nepal has been conducted.

This study aimed to determine the PAH concentrations and distributions in top soils from two sides of the Himalayas and identify the sources and the factors influencing their distributions, such as wind direction, altitude and land use. This study not only evaluated the possibility of PAH transport from Nepal and India to the TPC but also provided essential information for future studies of long-range transport and the cold trap effects of PAHs and their risks to human health.

2. Materials and methods

2.1. Study area

The Himalayas separate the TPC, from southeast Asian countries, including Nepal and India (Fig. 1A), and consist of a series of parallel and converging ranges covering an area of approximately 6×10^5 km^2. The climate system of the Himalayas between Nepal and China includes two parts, namely the Indian Monsoon system (from June to September) and the southern branch of the westerly winds (from November to March) (Wang et al., 2010). In the summer, the low pressure in this region drives air masses over India to the Himalayas, which normally results in significant precipitation. The distinct seasonal differences in wind direction and regional and orographic precipitation may be important for the atmospheric

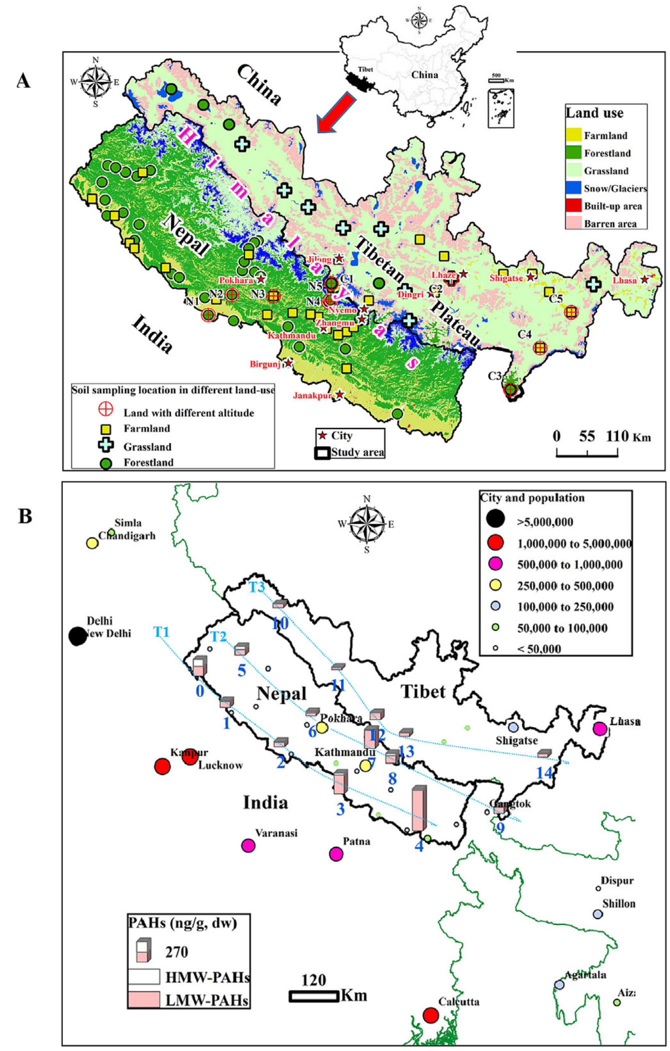

Fig. 1. Soil sampling locations from different land uses (A) and three transects (B) on the northern and southern sides of the Himalayas between China and Nepal. Distribution of LMW- and HMW-PAHs and total concentrations of PAHs are also given.

transport and deposition of compounds in this area. Several important cities and counties, including Dingri, Jilong, Nyemo, Shigatse City (the largest Chinese city in the study area), Kathmandu City (capital of Nepal), Pokhara and Birgunj (in Nepal) are located in the study area (Fig. 1A).

2.2. Soil sampling and chemical analysis

From June 2013 to March 2014, seventy-seven soil samples were collected from the Himalayan Mountains in China and Nepal based on land use, wind direction and altitude in the study area (Fig. 1A, B). In total, 30, 9 and 38 soil samples were collected from farm-, grass- and forest-lands, respectively, at altitudes of 45–5242 m (Table 4). Of the 77 soil samples, 50 were collected from the southern side of the Himalayas, Nepal (SSHN) at altitudes of 45–2763 m and the rest from the northern side of the Himalayas, China (NSHC) at altitudes of 1623–5242 m (Table 1).

To determine effects of wind on concentrations of PAHs, fifteen soil samples were collected from three transects. Along each transect, there was almost no local human activity, and the altitudes of the transect sites were approximately the same (Fig. 1B). Transect 1 (T1) had five numbered sites (marked 0–4) which were distributed