NATIONAL AFFAIRS

India

Delhi's Air Pollution

– (Re)distribution and Air Quality Regulations –

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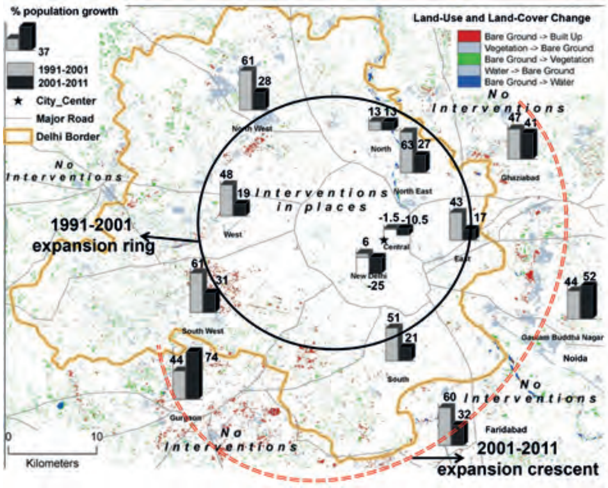
While the economies of the two Asian giants, India and China, have been thriving (Schuman, 2010), the increase in the burden of environmental contaminants and recent environmental interventions in these countries are drawing public attention. Beijing and Delhi have adopted radical measures for improving air quality. Beijing invested about US$10 billion to improve air quality in its preparations for hosting the 2008 Olympic Games (Chen *et al*., 2012; Chen *et al*., 2013), while in Delhi, polluting vehicles and industries were banned as mandated by the Supreme Court of India (Bell *et al*., 2004). While improvement in air quality in Beijing was short-lived and most effects of the interventions diminished after the Olympics (Davis, 2011; Chen *et al*., 2013), the policy interventions in Delhi were permanent and are still working (Narain and Krupnick, 2007; Kumar and Foster, 2009). Delhi became an exemplary city by enforcing the conversion of both commercial and public transport vehicles to compressed natural gas (CNG); closing polluting industries; and constructing the country's first modern metro system – Delhi Metro (Bell *et al*.; Agarwal and Zimmerman, 2008). At present, about 100,000 CNG-based vehicles are registered in Delhi, and more than 25,000 industries previously in residential areas have been relocated to the periphery of the city into three industrial estates or areas. While these interventions have received media attention (PTI, 2014; Harrismarch, 2015), we know little about their efficacy in improving air quality due to limited spatial coverage of air pollution monitoring inside and outside the city. Capitalising on high-resolution data – the 2-km Aerosol Optical Depth (AOD) data from the MODerate Resolution Imaging Spectroradiometer (MODIS) and the 30-m LULC (Land-Use and Land-Cover) from Landsat – this paper examines the level of air pollution before and after these interventions, and its association with LULC change.

Background

Delhi is home to 1.6 million people (Census of India, 2011) and its functional growth has continued unabated beyond its jurisdictional boundaries, especially in the southern and eastern parts (bordering Ghaziabad, Noida, Faridabad and Gurgaon) (Figure 1). Districts bordering Delhi experienced 1.5–3 times higher population growth between 2001 and 2011 than Delhi itself. Population growth in Gurgaon, located to the southwest of Delhi, was 73 percent as compared to 20 percent in Delhi (Census of India). The physical constraints on Delhi's further functional growth seem to have had a trickle-down effect, triggering land-use and land-cover changes in the areas outside Delhi (Figure 2).

Figure 1. Delhi and its adjacent areas, population growth between 1991–2001 and 2001–2011, and land-use and land-cover changes in the background



NOTE: According to the 2011 Indian Census, central Delhi experienced a 25 percent decline in population; and south-western and southern parts inside and outside Delhi experienced a more than 31 percent increase in population between 2001 and 2011.

Delhi has instituted several interventions to curb air pollution since 2000, including the conversion of public transport vehicles to CNG and closure of polluting industries. After these interventions (in Delhi), a large number of polluting vehicles and industries migrated to

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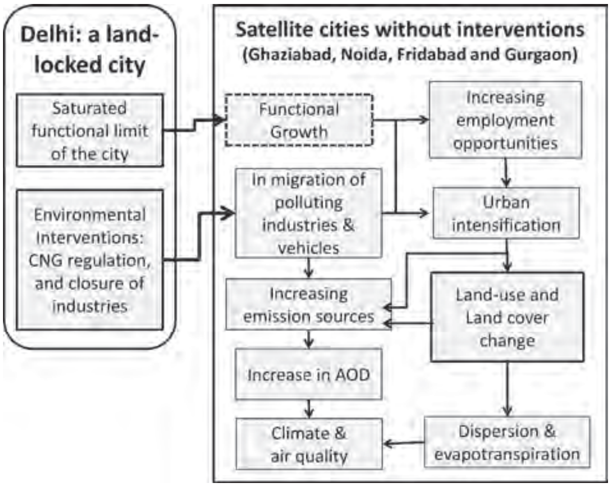
Figure 2. Environmental interventions, land-use and land-cover changes, and air pollution (re)distribution in and around Delhi – a conceptual framework



areas outside Delhi without similar controls (Kumar and Foster, 2007; Narain and Krupnick). With the influx of industries and foreign direct investment (FDI, including the establishment of many call centres), employment opportunities have been booming and urbanisation is intensifying in the satellite cities around Delhi (Bell *et al.*), hence the unprecedented population growth between 2001 and 2011 (Census of India).

Both urbanisation and air quality interventions are linked with LULC changes because of the increase in demand for housing and infrastructure development (Kumar, 2009). While the LULC changes can be held responsible for increases in emission sources, these processes also influence air pollution dispersion (Boddy *et al.*, 2005; Potoglou and Kanaroglou, 2005) and evapotranspiration (Figure 2) (Maes *et al.*, 2009; Gober *et al.*, 2010; Nakayama and Fujita, 2010). Based on the literature, we hypothesise that the LULC changes after the interventions (in Delhi) have resulted in air pollution (re)distribution inside and outside the city, meaning an improvement in air quality inside Delhi and deterioration of air quality outside the city. The remainder of this paper includes the methodology of our study, the results and discussion of the results, with reference to the relevant literature.

Methods and Material

Study Area

Delhi, the second largest city (after Mumbai) in India with a population of about 11 million and a geographic area of 1,500 km^2, was declared the world's most polluted city at the turn of the 21st century (Bell *et al.*). A recent report by the World Health Organization further suggests deteriorating air pollution in Delhi (WHO, 2014), with the highest concentration of fine particulates – $\leq 2.5\mu$m in aerodynamic diameter (PM$_{2.5}$). Localised adoption of radical measures to curb air pollution provides an excellent case study of the effects of air pollution policy on air pollution (re)distribution in emerging economies. The Supreme Court of India directed the Delhi Government to ban diesel and gasoline-based public transport vehicles (including buses and taxis) or convert them to compressed natural gas (CNG). The Supreme Court regulations were enforced in 2001–2002 (Narain, 2008). Moreover, about 25,000 polluting industries, based in areas meant for residential use only, were directed to three new industrial estates. Satellite cities in the south-western, southern, south-eastern and eastern parts of Delhi have accommodated industrial and residential development, including Gurgaon, Faridabad, Noida and Ghaziabad (Figure 1). It should be noted that air quality interventions that took place in Delhi did not apply to areas outside Delhi's jurisdictional boundaries. The literature suggests that Delhi and its neighbouring areas have witnessed increases in air pollution and population (Kumar and Foster, 2007; Narain; Census of India). Therefore, the chosen study area is important for assessing the trend of air pollution (inside and outside the city) before and after the interventions, and the association between levels of air pollution and LULC changes. It may shed light on the direct and indirect effects of environmental interventions on local and regional air pollution.

Data

Spatiotemporal coverage of air pollution inside and outside Delhi (especially before the Commonwealth Games in 2010) is sparse. There were seven monitoring stations with gaseous and particulate sensors in Delhi before 2010 but there was no monitoring site located outside Delhi. This research capitalises on high-resolution satellite-derived aerosol optical depth (AOD) to study spatiotemporal distribution of aerosols, calibrated for meteorological conditions as an indirect measure of air quality (Kumar *et al.*, 2008; Gupta and Christopher, 2009; Kumar *et al.*, 2011). AOD, retrieved using MODIS data, represents both anthropogenic and natural sources of aerosols integrated over the atmospheric column. When the contribution of natural sources of aerosols is removed, AOD shows a strong positive association with fine particulates (PM$_{2.5}$). Thus, AOD is an indirect proxy of air quality (Chen *et al.*, 2013; Kumar *et al.*, 2013). Moreover, annual trends of AOD can provide indirect measures of changes in air quality as sources of natural aerosols are unlikely to change dramatically, but anthropogenic sources of air pollution are changing with the growth in numbers of new vehicles and industries.

The high resolution 2-km AOD data were retrieved using the Level-1b MODIS radiance measurements acquired from the National Aeronautics and Space Administration (NASA) Level 1 and Atmosphere Archive and Distribution System (LAADS). A number of MODIS Level-2 products (MOD 03-geolocation, MOD 07-atmospheric profile, and MOD 35-cloud masks) were used in the retrieval process, similar to those for 10-km standard AOD products (NASA, 2009). Hourly meteorological data, including relative humidity, atmospheric pressure and temperature, were acquired from the US National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC, 2009). For extracting LULC types, cloud-free Landsat 5 TM data were obtained from the US Geological Survey (USGS) Global Visualization Viewer for February and March of 1998 (Path 40-41 and Row 146-7) as well as corresponding anniversary imagery from 2003 (USGS, 2009).

AOD Retrieval

The spectral channels used in retrieving AOD over land include 250m, 500m and 1km bands. The 250m (0.66 and 0.86µm) bands were used to detect water bodies (such as lakes, rivers, *etc*.). Combinations of 500m (0.47µm) and 1km bands (1.38, 4.7, 15µm) were used for cloud detection. The aggregated 0.66µm and 0.86µm channels together with other 500m channels (0.47, 0.55, 2.13µm) were used to derive AOD. The methodology for retrieving the standard 10km AOD retrieval is detailed elsewhere (Remer *et al*., 2006). To retrieve the 2km AOD, we used the C51 MODIS aerosol retrieval algorithm, but with a more restrictive criterion for the selection of pixels. Since the maximum number of pixels available in a 2 x 2 km grid was only 16, we set the minimum requirement for good (cloud-free, water-free, dark) pixels to 2. The methodology for the 2km AOD retrieval and its comparison with the coarse resolution (*i.e.*, 10km AOD) can be found in Kumar (2011).

Land-Cover Change

LULC for the years 1998 and 2003 was classified for Delhi and for a surrounding region encompassing an area of approximately 118,000 km^2. The six visible (0.43µm to 0.68µm) and near infrared bands (0.77µm to 0.99µm) of the annual four images were mosaicked. The 1998 and 2003 mosaics were then stacked to produce a 12-band image. Vegetation in 2003 was thresholded with the aid of the Normalized Difference Vegetation Index. To improve spectral separability, a Principal Components Analysis (PCA) was applied for the vegetated and non-vegetated scenes separately (Deng *et al*., 2008; Henry, 2008). The first five bands (1–5) of each PCA accounted for the majority of the variance (~90 percent). These bands were clustered using a K-means algorithm initialised with 30 clusters (ITT Visual Information Solutions, 2009). The resulting clusters were labelled as six land-cover categories and the corresponding 1998–2003 change classes based on IRS-1C (Indian Remote-sensing Satellite-1C) panchromatic 5.8 m resolution data (resampled to 6.25m) and Digital Globe (DG) high-resolution imagery provided by Google Earth (Monkkonen, 2008). Independent validation data were derived from the DG imagery as well as the IRS-1C data. The accuracy of Land Cover (LC) classification was found to be 93 percent and 87 percent for the overall LC classification and the LC change, respectively (Table 1). Ancillary data consisting of polylines and polygons of roads and industrial parks were acquired from the Survey of India and combined with the thematic classification. Road polylines were encoded at 30m resolution irrespective of thematic class. Industrial areas were overlaid on the thematic classification and were identified as a separate class where the polygons intersected the built thematic class.

Table 1. LULC type and change validation

1998 -> 2003 LULC change accuracy		Unchanged LULC accuracy	
Class	**% Correct**	**Class**	**% Correct**
Bare soil-> Urban	91.6%	Urban	92.3%
Vegetation -> Bare soil	92.3%	Residential	100.0%
Bare soil -> Vegetation	100.0%	Light residential	100.0%
Water -> Bare soil	92.3%	Bare soil	94.4%
Bare soil -> Water	60.0%	Vegetation	100.0%
		Water	64.7%
		Industrial	100.0%
Average	**87.3%**	**Average**	**93.1%**

Although there are various measures of gaseous and particulate pollution, these data were not monitored at enough sites, and not available for the areas outside Delhi. Thus, we relied on 2km AOD, which showed stronger agreement with ground monitored AOD (at AERONET sites) than the 10km AOD and a good proxy of fine particulates ($PM_{2.5}$) (Kumar *et al*., 2011).

Collocation

The data used in this study come from three different sources with different spatial and temporal resolutions. MODIS AOD has a spatial resolution of 2km at nadir at 10:30 and 13:30 LST (local solar time) from 2000 to 2004. The 30m LULC data are available at 10:00 (equatorial crossing time) in 1998 and 2003. Meteorological data were hourly estimates at point locations. Let L_{ik} denote a 30m pixel at i^{th} location (represented by a pair of coordinates) with k^{th} LULC type. AOD_{MODIS} retrievals were distributed sporadically (with the repeated path every 16th day) and did not correspond with the location and time of LULC data. Let τ_{atp} denote AOD from MODIS (onboard Terra satellite) at locations, $a=1,\ldots,A$, days $t = 1,\ldots,T$, and satellite overpass time (or hour of AOD_{MODIS}; $p=1,\ldots,P$). On a given day, τ_{at} was observed at multiple locations (a), whereas there were many 30m LULC pixels around the

a^{th} site just for two days (in 1998 and 2003). The overpass (or recording) time (p) of AOD_{MODIS} did not correspond with the duration and time (h) of meteorological data (Mh) on the corresponding day.

Instead of assigning the same value of τ_{at} to all LULC pixels, we estimated the proportion of area under k^{th} LULC type around a^{th} location (L_{ak}) by dividing the number of pixels under k^{th} LULC type by the total number of pixels within a 1km radius of a^{th} location. Meteorological estimates at a^{th} location and p^{th} overpass time (M_{ap}) were derived by averaging the meteorological data at all stations within a 90-minute time interval of the p^{th} overpass time of AOD_{MODIS} data on t^{th} day. The final disaggregated dataset consisted of 703,756 unique AOD values (from 2000–2004) collocated with percentage of area under different LULC and meteorological conditions. These data were grouped into two time periods: 2000–2001 (pre-intervention period) and 2003–2004 (post-intervention period). The year 2002 was skipped, because it was the year of transition when most air quality interventions were implemented. Yearly LULC data were further aggregated into 1km grids (~6,450 pixels) over the study area. The closest 2km AOD values were assigned to 1km grid points. Subsequently, AOD data were averaged by 1km grid cell for pre- and post-intervention periods to examine changes in the AOD.

Spatial Autoregressive Models

Conditional autoregressive modelling was employed to examine the effects of LULC types, LULC changes and environmental covariates on AOD. In the aggregated dataset, let τ_a be the average AOD corresponding to a^{th} pixel (a = 1, …, N). Likewise, percentage of area under each LULC type and meteorological conditions were averaged for a^{th} pixel. Assuming averaging these for the entire duration accounts for the temporal noise, τ_a can be written as a function of LULC type (L_a) and average meteorological conditions (M_a) as

$$\tau_a = a + \beta L'_a \partial + \quad M'_a + u_a + \varepsilon_a \qquad (1)$$

where β and ϕ are regression coefficients, u_a is the spatial random effect assessed using conditionally autoregressive model as suggested by Besag (1974)

$$u_a \mid u_j \quad \sim \quad N \quad \frac{\rho}{\sum_{j=1}^{k} w_{aj}} \sum_{j=1}^{k} u_j w_{aj} \;, \; \frac{\sigma^2}{\sum_{j=1}^{k} w_{aj}} \qquad (2)$$

where ρ is the spatial autocorrelation parameter; $w_{aj} = 1$ if j is a neighbour, = 0 otherwise. The decision about neighbours can be guided by an empirical variogram, which graphs the average semivariance on the y-axis and distance interval on the x-axis. The sill value that levels off when the spatial autocorrelation becomes insignificant can help us choose the distance range within which spatial autocorrelation exists, referred to as the screen effect (Journel and Huijbregts, 1978; Cressie, 1993). The spatial random effect has the following joint distribution

$$u \sim N_n\,(0, \sigma^2\,(\boldsymbol{I} - \rho \boldsymbol{W})^{-1}) \qquad (3)$$

where N_n is the n-dimensional normal distribution, I is an $n \times n$ identity matrix and $\boldsymbol{W}$ is the weight (or adjacency) matrix, which can be replaced by an inverse distance weighted matrix, in which j^{th} neighbours close to a^{th} location are given higher weight and *vice versa*.

Results

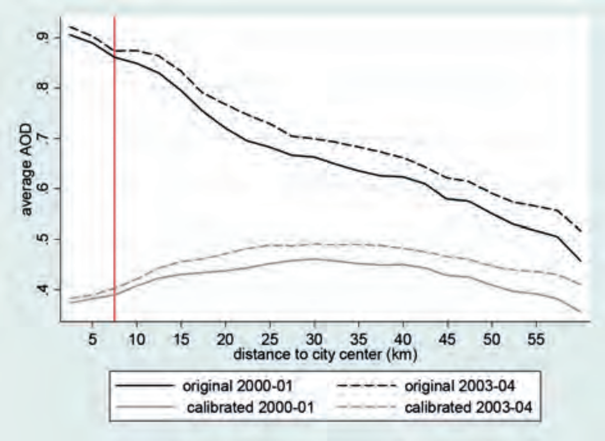
This research focuses on Delhi and its surrounding areas within a 0.36 degree (or ~32km) distance from Delhi's border. The average AOD in the study area was 0.674 (±0.001 at 95 percent confidence interval) and declined with the increase in distance from the city centre (Figure 3 and Table 2). The overall AOD in the study area was 6–7 times higher than that observed in less polluted areas including the US (Kumar *et al*., 2011). For example, the average AOD monitored at 16 sparsely distributed AERONET sites in the continental US was 0.0998±0003 (NASA, 2007) as compared to 0.674 AOD value in the study area between 2000 and 2004. The areas outside Delhi experienced a 1.7 percent higher increase in AOD between 2000–2001 and 2003–2004 (Table 2). A visual inspection of Figure 4 suggests that the bordering areas (both inside and outside) of Delhi witnessed a significantly higher increase (0.12; $p < 0.001$) in AOD after the interventions.

The increase in AOD (between 2000–2001 and 2003–2004) corresponded with the increase in distance from the city centre (Figure 3): the increase in AOD

Table 2. Change in AOD with respect to distance from the city centre

Distance to city centre (km)	2000–2001 Mean	2003–2004 Mean	% Change between time periods
10	0.863	0.885	2.553
20	0.766	0.799	4.229
30	0.675	0.704	4.275
40	0.633	0.664	4.815
50	0.584	0.608	4.158
> 50	0.512	0.545	6.551
Total	**0.653**	**0.682**	**4.457**

Figure 3. Change in AOD and calibrated (for meteorological conditions) AOD before and after the air quality interventions in and around Delhi



within 10km of the city centre was less than 2.5 percent, whereas the increase in AOD in areas more than 50km away from the city centre was more than 6.5 percent (Table 2). This suggests a significant increase in aerosol loading from anthropogenic sources in the peripheral areas after the interventions, because natural sources of aerosols (such as water vapour and sea salt during the monsoon period and dust storms from the Thar Desert during the pre-monsoon periods) are unlikely to change during the same time period.

Of the total geographic area under investigation, only 7.3 percent of the area underwent changes between 1998 and 2003 (Table 2). The LULC changes were grouped into four categories: 1) bare ground to built-up, 2) vegetation to bare ground, 3) bare ground to vegetation, and 4) net loss of vegetation canopy cover. Both LULC types and AOD show spatial heterogeneity before and after the interventions (Figures 4, 5, 6 and 7). In the south-eastern (near Noida) and south-western (near Gurgaon) bordering areas of Delhi, AOD was relatively high (> 1). The northern and north-western parts of Delhi were largely vegetated (primarily under crops during the spring season) as these areas of the city have remained rural and rely on agriculture. From the visual description, spatial patterns emerged in the rate of change in both LULC and AOD: 1) Central parts of the city showed a decline in AOD, and 2) the bordering areas of

Figure 4. AOD concentration, 2000–2001

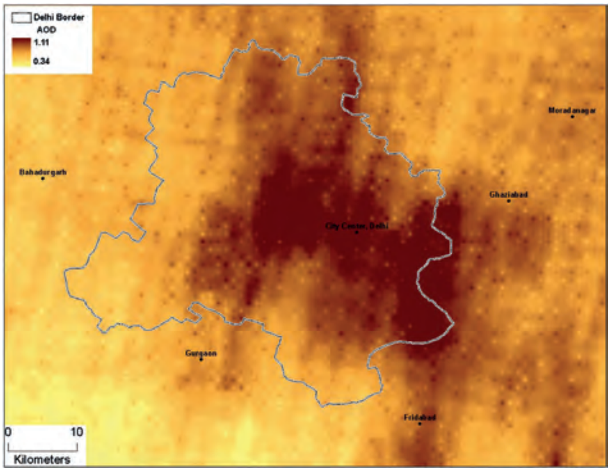


Figure 5. AOD concentration, 2003–2004

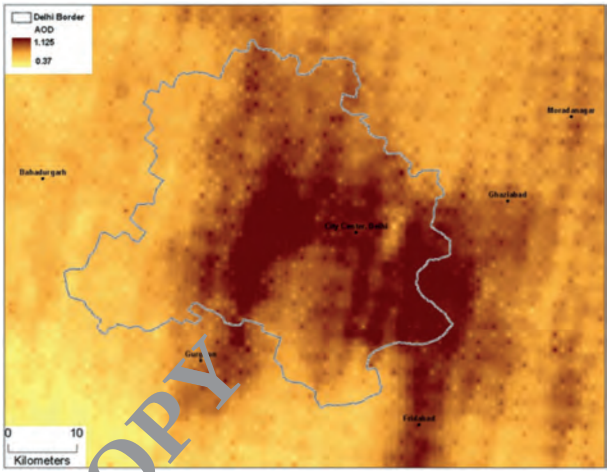


Figure 6. Land-use and land-cover types, 1998

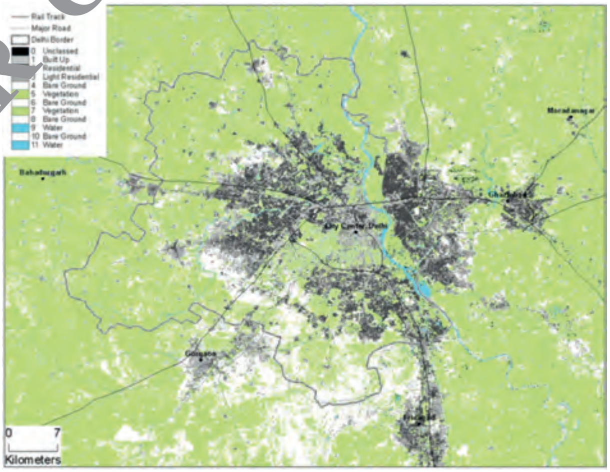


Figure 7. Land-use and land-cover types, 2003

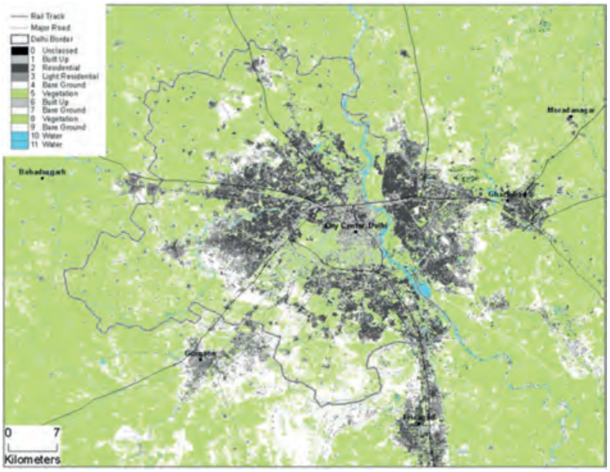


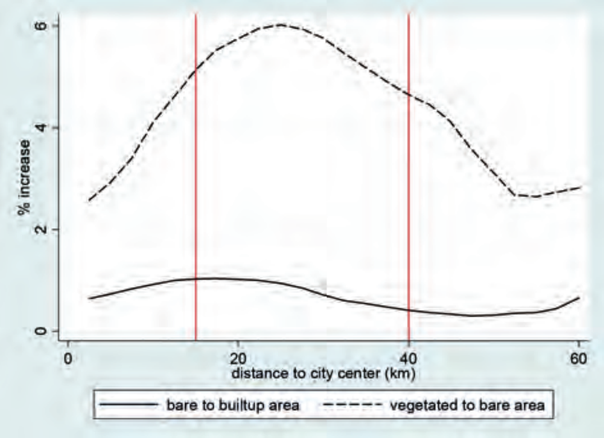
Table 3. AOD, LULC types, and changes in and around Delhi MSA – Summary Statistics

	Delhi	Outside Delhi	Both
Aerosol optical depth (AOD), 2000–2001	0.753±0.004	0.630±0.002	0.653±0.002
Aerosol optical depth (AOD), 2003–2004	0.790±0.004	0.672±0.002	0.695±0.002
% Change in AOD between time periods	5.021221	6.789855	6.334561
Dew point (degree C)	14.593±0.007	13.912±0.033	14.057±0.030
Unchanged LULC Type (% area under)			
Industrial clusters	0.366±0.001	0.095±0.005	0.153±0.006
Major roads	0.577±0.002	0.069±0.004	0.178±0.008
Minor roads	1.543±0.004	0.511±0.016	0.731±0.019
Bare ground	15.252±0.045	12.468±0.238	13.062±0.212
Vegetation	45.469±0.090	72.758±0.365	66.936±0.440
Water	1.028±0.003	0.508±0.011	0.619±0.013
Residential	12.877±0.039	2.356±0.096	4.601±0.154
Light residential	7.936±0.011	2.704±0.057	3.820±0.073
Built-up	7.548±0.028	1.205±0.042	2.558±0.093
Total - Unchanged LULC type	**92.596**	**92.676**	**92.659**
LULC change from 1998–2003			
Changed from bare ground to built-up	0.990±0.003	0.597±0.012	0.681±0.012
Changed from vegetation to bare ground	4.885±0.006	4.769±0.042	4.794±0.036
Changed from bare ground to vegetation	1.214±0.003	1.740±0.014	1.627±0.013
Changed from water to bare ground	0.176±0.001	0.102±0.003	0.118±0.003
Net loss of vegetation canopy cover	3.674±0.005	3.107±0.004	3.214±0.004
Changed from bare ground to water	0.139±0.000	0.116±0.003	0.121±0.002
Total – LULC change from 1998–2003	**7.404**	**7.324**	**7.341**
GRAND TOTAL	**100**	**100**	**100**

Standard errors in the second row, *** $p<0.01$, **$p<0.05$

Delhi showed a significant increase in AOD. Areas around Delhi and Gurgaon (border) showed an increase in built-up area and greater than 0.1 increase in AOD (*i.e.*, about 14.9 percent of the average AOD value in the entire study area) after the interventions. The rate of increase in the built-up area and loss of vegetation canopy cover (between 1998 and 2003) was highest at around 17km (*i.e.*, average distance from Delhi's border to the city centre) (Figure 8). The central district of Delhi experienced a 25 percent decline in population between 2001 and 2011 in contrast with a 73 percent increase, during the same period, in the population in Gurgaon – southwest of Delhi's border. A visual inspection of Figure 4 further suggests that the areas with a significant increase in AOD, especially the south-western parts (inside and outside Delhi), closely correspond with a significant increase in built-up areas.

Figure 8. Change in bare ground to built-up area and vegetated to bare area from 1998 and 2003 in and around Delhi



Change in AOD was examined with respect to LULC types and changes using a spatial autoregressive model: Tables 4, 5 and 6. Three important findings emerged from this analysis. Firstly, among the four categories of LULC changes, conversion of bare ground to built-up area was the only significant predictor of increase in AOD in a univariate model (Table 4). In the multivariate model, which included control for meteorological conditions, all four categories of LULC changes emerged as significant predictors of change

Table 4. Change in AOD with respect to change in LULC

Variables	Only LULC change and AOD				LULC change and other variables			
	Bare ground to built-up	**Vegetation to bare ground**	**Bare ground to vegetation**	**Net loss in vegetation**	**Bare ground to built-up**	**Vegetation to bare ground**	**Bare ground to vegetation**	**Net loss in vegetation**
Change in LULC	0.0263**	0.0439	0.0015	-0.0003	0.0293**	0.0019**	-0.006**	0.00316**
	0.0018	0.0038	0.0020	0.0007	0.0039	0.0007	0.0021	0.0007
Change in dew point (°C)					0.0217**	0.0226**	0.0227**	0.0226**
					0.0006**	0.0006	0.0006	0.0006
Distance to border (km)					0.0950	0.0822**	0.0841**	0.0671**
					0.0148	0.0168	0.0163	0.0017
Distance to city centre (degree)					-0.0525	-0.0927	-0.088	-0.069**
					0.0131	0.0151	0.0150	0.0168
Intercept	0.025**	0.0439**	0.0406**	0.0441**	0.0283**	0.053**	0.0718**	0.0468*
	0.0022	0.0038	0.0035	0.002	0.0039	0.006	0.0034	0.0058
Auto-regressive term	.148**	0.03	0.031	0.031	.378**	0.239**	.2438**	0.247**
AIC	-12784	-12649	-12650	-12649	-14000	-13824	-13828	-13833

in AOD. Increase in built-up area and loss of vegetation canopy cover were positively associated with the increase in AOD and *vice versa* (Table 4). In contrast, the areas with an increase in vegetation canopy cover recorded a significant decline in AOD.

Secondly, the spatial distribution of AOD showed a significant association with LULC types and changes. In the full multivariate model, LULC types and changes, meteorological conditions and other ancillary variables together explained ~90 percent of the total spatial variability in AOD (Table 6, following this article).

Thirdly, distance from Delhi's border (for areas outside Delhi) and the distance from the city centre were positively associated with the rate of increase in AOD after the interventions (Table 2, and Figures 3 and 8). This clearly suggests an intensifying burden of air pollution with the increase in distance from the city centre, especially to the east, south and south-west.

Discussion

This paper provides insights into how environmental interventions have resulted in LULC changes and air pollution (re)distribution. It is evident that the increase in AOD inside the city was significantly lower than that outside the city while the central parts of the city witnessed a decline in AOD after the interventions. The main benefits of these interventions were restricted to the central parts of the city, and these interventions were also effective in containing further deterioration in air quality inside Delhi (Kumar and Foster, 2007; Kumar and Foster, 2009). However, the areas outside the city, which were not subject to these interventions, experienced a disproportionately higher increase in AOD. The rate of increase in AOD after the interventions went up with the increase in distance from the city centre: with every 2.5km, the increase in the rate of AOD between 2000–2001 and 2003–2004 was 0.13 percent ($p > 0.0001$). This suggests intensifying emission sources with distance from the city centre. Changes in AOD in the study area between 2000–2001 and 2003–2004 corresponded with the change in population between 2001 and 2011. The central part of the city showed a decline while peripheral parts showed an increase in both AOD and population concentration. After the interventions, spatial distribution of AOD and change in AOD closely corresponded with the spatial distribution of LULC types and change in LULC types. This helps us understand two important processes that are at work in the study area. First, small changes in LULC result in substantial changes in AOD; for example, the total increase in built-up areas, largely concentrated in the southern parts of the study area, was 0.68 percent, and the increase in AOD in these areas was more than 0.1 (~14.9 percent of the average AOD value). Second, LULC changes that can be associated with the changes in emission sources are important agents of change in AOD. The interventions were effective in the central parts of the city as expected. However, areas outside Delhi not subject to these interventions experienced deteriorating air quality. As the literature suggests, emission sources have increased disproportionately in these areas due to the influx of polluting industries and vehicles, and urban intensification after the interventions that took place in Delhi (TERI, 2001; Kumar and Foster, 2009). This, in turn, can explain an increase in AOD. Since Delhi seems to have attained its limit for (further) functional and economic growth, newer growth and investment is being directed to areas outside Delhi. Population growth in Delhi between 2001 and 2011 was 21 percent as compared to more than 30 percent (and 73 percent in Gurgaon) increase in population in the bordering districts for the same duration (Census of India). These numbers indeed confirm that most functional growth is taking place in the bordering districts outside Delhi.

Table 5. Factor loading of LULC type

LULC Type	Factor 1 Urbanness	Factor 2 Bare ground	Factor 3 Water	Factor 4 Deforested	Factor 5 Suburban	Uniqueness
LULC type that did not change from 1998 to 2003						
Industrial	0.9197	0.0463	0.0817	0.1736	-0.0386	0.1137
Major roads	0.9509	0.1921	0.114	-0.1251	0.0093	0.0302
Minor roads	0.9316	0.1555	0.0183	0.2632	0.0612	0.0346
Bare ground/surface	0.019	0.9641	-0.1103	0.0288	-0.0792	0.0508
Vegetation	-0.754	-0.6066	-0.0747	-0.1109	-0.1403	0.0258
Water	0.8419	-0.2279	0.3055	0.1762	-0.0287	0.114
Densely residential	0.9528	0.1157	0.184	0.0074	0.1531	0.0214
Light residential	0.7329	0.3532	0.1004	0.1351	0.5525	0.0045
Built-up area	0.9468	0.1063	0.1516	-0.1531	0.0944	0.037
Change in LULC from 1998 to 2003						
Bare ground to built-up area	0.2478	0.8633	0.0529	0.1604	0.2361	0.109
Vegetation to bare ground	0.064	0.1221	0.0939	0.9777	0.0337	0.0152
Bare ground to vegetation	-0.544	-0.4275	-0.5008	0.0642	0.0123	0.2662
Water to bare ground	0.2161	-0.3083	0.7308	0.1338	0.1672	0.2783
Bare ground to water	0.1704	0.0785	0.7916	0.1042	-0.0538	0.3244
Proportion of total variance	0.5171	0.2019	0.1256	0.0942	0.0355	NA
Cumulative proportion of variance	0.5171	0.719	0.8446	0.9388	0.9742	

The results of this paper clearly suggest redistribution of air pollution. LULC types and LULC changes (affected by urbanisation, urban intensification and economic growth), along with ancillary variables, explain 90 percent of the total spatial variability in AOD. However, this finding should be interpreted with caution, because there is no direct mechanism to attribute these changes in AOD to air quality interventions in Delhi in the absence of a complete inventory of individual emission sources before and after the interventions. Nonetheless, an increasing rate of change in both LULC and AOD with respect to distance to the city centre points toward urban intensification in the peripheral areas of Delhi. Gurgaon, southwest of Delhi, which experienced a 73 percent increase in population between 2001 and 2011 (Census of India), has been successful in attracting FDI during the past decade (Government of India, 2009). This satellite city is home to many call centres and manufacturing plants. While such activities can directly be linked with an increase in built-up areas due to an increase in the demand for housing and infrastructure services, it is difficult to disentangle the effects of air quality interventions implemented in Delhi from other processes that have been important agents of LULC changes (Mookherjee and Geyer, 2011). For example, market forces and the policies of neighbouring states (particularly Haryana) have played an instrumental role in creating employment opportunities and attracting FDI (Mahadevia, 2006).

Further research needs to focus on differentiating between the effects of environmental interventions in Delhi and the market forces and policies of neighbouring states to evaluate the association between LULC changes and their effects, in turn, on AOD (or air quality) (re)distribution. The findings of this research have important implications for respiratory health, and the way environmental policies are implemented. Our analysis suggests that very small changes (7.8 percent) in LULC were associated with the significant changes in AOD (4.8 percent). A recent study suggests that the respiratory health (measured by lung function) of Delhi residents showed some improvement. However, the respiratory health of non-Delhi residents has deteriorated (Brown University, 2011; Foster and Kumar, 2011). Policy makers should be called upon to monitor and respond to the unremitting increase in air pollution in areas outside Delhi. An important lesson learned from this research is that the lack of uniform policy interventions can result in disproportionate distribution of emission sources (and hence air pollution) and LULC changes.

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Table 6. Combined effects of different LULC types and changes and meteorological conditions on (yearly aggregates of) AOD using ordinary least square regression and conditional autoregressive models

Covariates	OLS	CAR
Urbanness	0.0569***	0.067***
	-0.0012	0.002
Bare ground	-0.0113***	-0.0105***
	-0.00075	0.0015
Water	0.00571***	0.0146***
	-0.00071	0.0016
Deforested	0.00628***	0.0171***
	-0.00081	0.00155
Suburban	0.0393***	0.0363**
	-0.00087	0.0016
Dew point (°C)	0.0468***	0.0277***
	-0.00084	0.0007
City context (1=Delhi, 0 otherwise)	-0.00539**	-0.0025***
	-0.00283	0.0037
Autoregressive term	NA	0.904***
		NA
Constant	0.0123	0.2798
	-0.0119	0.0106
Observations	6450	6450
R-squared	0.789	NA
Robust standard errors in the second row of each variable: *** p<0.01, ** p<0.05, * p<0.1		

NA = not applicable or could not be estimated

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North Korea

Green Diplomacy

– An Opportunity for Peace-building? –

by Rakhyun E. Kim* and Saleem H. Ali**

International environmental agreements have historically been considered to be in the realm of "low politics", disconnected from the "high politics" of war and peace.[1] There is growing evidence, however, suggesting that, if the issues are framed appropriately with a scientific exchange, and mediation, ecological factors can foster cooperation between perceived adversaries.[2] Multilateral environmental mechanisms thus deserve further study in the context of regimes that have otherwise appeared resistant to, or reticent in, cooperating on issues of high politics. Although they might not lead to a full resolution of extant conflicts, such issues might provide an opportunity to understand part of the executive's decision-making processes in isolated States, and possibly indicate ways in which environmental diplomacy could pave the way for broader engagement in international dispute resolution.[3]

The Democratic People's Republic of Korea (DPRK) is commonly perceived as one of the most secretive and uncooperative countries in the international community. A notable example is its withdrawal from the Treaty on the Non-Proliferation of Nuclear Weapons in 2003, and subsequent development of nuclear weaponry. In the field of sustainable development, however, the DPRK's cooperation with other States and international organisations has seemingly improved over time. While lacking in technical and financial capacity,[4] the DPRK has joined a number of international environmental agreements and implemented various measures to fulfil its obligations as a contracting party.[5] Some commentators have observed that the DPRK's documentation, in reporting to the three Rio Conventions, for example, has steadily improved in quality and detail over the past decade as a consequence of its institutional participation.[6]

Against this backdrop, the research described in this article presents an overview of the DPRK's international environmental cooperation. The key research questions are:

- When and in which issue areas has the DPRK formally cooperated with other States?
- How has the DPRK implemented its international environmental obligations? and,
- (to the extent answerable) Why has the DPRK cooperated in those chosen issue areas? We also explore the hypothesis that "green diplomacy" might provide an opportunity to overcome the current impasse between the West and the DPRK.[7]

Ultimately, this research aims to shed light on possible strategies to enhance the environmental performance of the DPRK, and promote peace and stability in Northeast Asia and beyond.

There are at least three reasons why a review of the current state of the DPRK's international environmental cooperation is timely and necessary. First, the international community has a shared responsibility to support developing States to better protect their environment from unsustainable practices. Given the DPRK's current economic hardship,

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