Air Quality and Human Health Impacts of Grasslands and Shrublands in the United States

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Abstract

Vegetation including canopy, grasslands, and shrublands can directly sequester pollutants onto the plant surface, resulting in an improvement in air quality. Until now, several studies have estimated the pollution removal capacity of canopy cover at the level of a county, but no such work exists for grasslands and shrublands. This work quantifies the air pollution removal capacity of grasslands and shrublands at the county-level in the United States and estimates the human health benefits associated with pollution removal using the i-Tree Eco model. Sequestration of pollutants is estimated based on the the Leaf Area Index (LAI) obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) derived dataset estimates of LAI and the percentage land cover obtained from the National Land Cover Database (NLCD) for the year 2010. Calculation of pollution removal capacity using local environmental data indicates that grasslands and shrublands remove a total of 6.42 million tonnes of air pollutants in the United States and the associated monetary benefits total $268 million.

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Human health impacts and associated monetary value due to pollution removal was observed to be significantly high in urban areas indicating that grasslands and shrublands are equally critical as canopy in improving air quality and human health in urban regions.

Keywords: Air Pollution Removal, Grasslands and Shrublands, Ecosystem Services, Health Benefits, Air Quality

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1. Introduction

Emissions of air pollutants from anthropogenic and natural sources including Carbon Monoxide (CO), Nitrogen Dioxide (NO_2), Ozone (O_3), Sulfur Dioxide (SO_2) and Particulate Matter (including PM_{10} and $PM_{2.5}$) have a significant impact on the health and well-being of individuals. A recent report by the American Lung Association indicated that at least 166 million people in the US still live in counties where unhealthful levels of air pollution exists (Association (2016)). Air pollution related illnesses include respiratory diseases, pulmonary illness, and cardiovascular diseases (Pope III et al. (2002)), mainly due to emissions of $PM_{2.5}$ and O_3. Studies have estimated that premature death due to changes in $PM_{2.5}$ and O_3 concentration from combustion related emissions is estimated to be about 200,000 and 10,000 per year, respectively (Caiazzo et al. (2013)). Emissions of these pollutants from anthropogenic sources such as road transportation, power generation, and industrial emissions are the largest contributors for pollution related mortalities and premature mortalities.

Vegetation including canopy, grasslands, and shrublands has the capacity to provide societal and environmental benefits by providing services such as improving air quality, sequestering carbon, reducing air temperature and improving energy conservation in buildings (Nowak and Crane (2002); Nowak et al. (2006a, 1998, 2013)). Removal of air pollutants directly from the atmosphere by vegetation results in an improvement in ambient air quality thus reducing incidences of respiratory, pulmonary and cardiovascular diseases. Gaseous pollutants like NO_2, SO_2 and O_3 are directly absorbed on the vegetative surface and these molecules diffuse into the inter-cellular spaces in the leaf. Particulate matter gets intercepted by the vegetative surface, some of which gets re-suspended back to the atmosphere while some drops to the ground with leaf fall. Thus, there is a need to better understand the environmental benefits provided by different land categories to protect and preserve multiple ecosystem services, especially air quality regulation service.

Several studies have estimated the air pollution removal and carbon sequestration benefits for a unit canopy cover at the county level based on the total tree cover, percentage of evergreen trees, leaf area index and the local ambient air pollution concentration (Hirabayashi et al. (2012); Nowak et al. (2014); Nowak and Crane (2002); Hirabayashi (2014); Nowak et al. (1998); Hirabayashi and Nowak (2016)). Nowak et al., 2006 (Nowak et al. (2006b)) estimated the total pollution removal by urban trees to be about 711,000 tonnes per year. These studies also estimate the monetary benefits associated with improvement in air quality based on U.S EPA's Benefits Mapping And Analysis Program (BenMAP) (EPA) (2012a)) values. BenMAP estimates incidences of adverse health effects and the monetary values associated with changes in air pollution concentration.

In addition to canopy, grasslands and shrublands are other important vegetation classes that can have an impact on air quality and human health. Until now, several studies have estimated the carbon storage and sequestration capacity of grasslands and shrublands in various regions in the US (Schuman et al. (2002); Conant et al. (2001)) but no such study estimates their air pollution sequestration capacity. This study estimates the air pollution removal benefits of NO_2, O_3, $PM_{2.5}$ and SO_2 by grasslands and shrublandss at the county level. The study also links pollution removal with improved health benefits and estimates the associated monetary value. Determination of pollution removal by grasslands and shrublands is primarily based on the area of each land category, daily leaf area index and the hourly pollution concentration while health effects and monetary benefits are calculated based on the BenMAP values.

2. Methods and Models

Air pollution removal, avoided health impacts, and monetary benefits due to improvement in air quality through sequestration of pollutants by grasslands and shrublands were calculated in four ways. All calculations were carried out for the lower 48 states and Washington DC in the conterminous US for the year 2010. First, the total grassland and shrubland cover in the US was determined using the National Land Cover Database (NLCD) 2011 database. Secondly, the daily leaf area index for each state was obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS)-derived dataset of LAI. Next, the pollutant flux value for each land classification was determined using the i-Tree Eco model, and finally the health impacts and monetary values due to the change in NO_2, O_3, $PM_{2.5}$, and SO_2 concentration was estimated using the BenMAP model (EPA) (2012a)). All the analyses were performed separately for grasslands and shrublands at the county level for all urban and rural areas in each county. Land areas in each county were associated with a rural and urban parameter index depending on the 2010 Census data, with rural land areas defined as land parcels with a population of less than 2,500 (Bureau. (2013)).

2.1. Land cover estimates and vegetation parameters

Land cover estimates of rural and urban grasslands and shrublands were obtained from NLCD 2011 (Homer et al. (2015)). These include land areas classified as "Grasslands and Herbaceous Land" and "Shrub and Scrub Land". The maximum LAI for each land category was estimated from the MODIS-derived biophysical parameter (Zhao and Jackson (2014)) on a daily basis. This MODIS-derived dataset estimates the LAI of vegetation classes using the International Geosphere-Biosphere Programme (IGBP) land classification scheme and the LAI for land types classified as closed shrublands (Type 06), open shrublands (Type 07) and grasslands (Type 10) were used to calculate the sequestration rate.

The biophysical variable LAI has a temporal scale of 8-day period for the years 2000-2012 with a spatial resolution of 0.05 degree (approx. 5 km). All the pixels that were covered with snow during the measurement of LAI were eliminated while synthesizing the maps. Each pixel in the dataset contains an array of 46 entries, representing 8-day averages for a one-year period and the daily LAI parameters were estimated at the state scale based on the number of pixels within the boundary of each state. State-wise LAI numbers were then estimated based on the median LAI value of all pixels for each 8-day period.

To eliminate outliers due to measurement errors, a robust local regression smoothing using weighted linear least squares with a first degree polynomial model was applied. Daily LAI values at the state-level were then linearly interpolated for Jan 1 to Dec 27 based on the 8-day average values. LAI values for the last four days between Dec 27 - Dec 31st were then linearly extrapolated. One of the primary reasons for linearly interpolating the LAI values is because of the lack of availability of growth curves for grasses and shrublands individually. Since the LAI values are measured inputs to the model, these numbers indirectly capture the seasonal variation and different growth rates for grasslands and shrublands.

Pixels for estimating the LAI were available only for a total of 25 states for grasslands and 16 states for shrublands. LAI values for the remaining states were estimated by averaging the LAI for neighbouring states belonging to the same climatic zone. States were classified into different climatic zones based on the climatological map developed by the National Oceanic Atmospheric Administration (NOAA) (Figure S1). For some climatic zones where no pixels were available for any state (eg. East North Central states for grasslands), average LAI values for all the surrounding neighbouring states were used. Figure S1 shows the states where the LAI values for grasslands were obtained either from measured data (blue) or calculated using climate averages (orange). For shrublands, LAI values for states in the central and northeastern part of the country could not be estimated based on the climatic averages due to very sparse data, resulting in a value of zero LAI in some regions as shown in Figure S2.

It is important to note that lack of data on shrubland LAI in these regions results in an underestimation of the capacity of shrublands to sequester pollutants even though the percentage of shrubland cover in some states is $> 0\%$ as shown in Table S2.

2.2. Air pollution removal by vegetation

The i-Tree Eco model (Service (2016)) was used to estimate the pollutant sequestration rates of grasses and shrubs, based on the county-level grass or shrub cover, state-level hourly LAI interpolated from the daily LAI, county-level meteorological and air pollution data for the year 2010 as shown in Figure 1.

Model runs for rural and urban areas were performed individually based on the 2010 Census classification. Hourly pollutant flux F ($gm^{-2}h^{-1}$) was estimated as

$$F = V_d C \tag{1}$$

where V_d is the deposition velocity on the vegetative surface in (mh^{-1}) and C is the local ambient pollution concentration in (gm^{-3}). The deposition velocity is calculated as an inverse sum of the aerodynamic (R_a), quasilaminar boundary layer (R_b) and canopy resistances (R_c) as,

$$V_d = (R_a + R_b + R_c)^{-1} \tag{2}$$

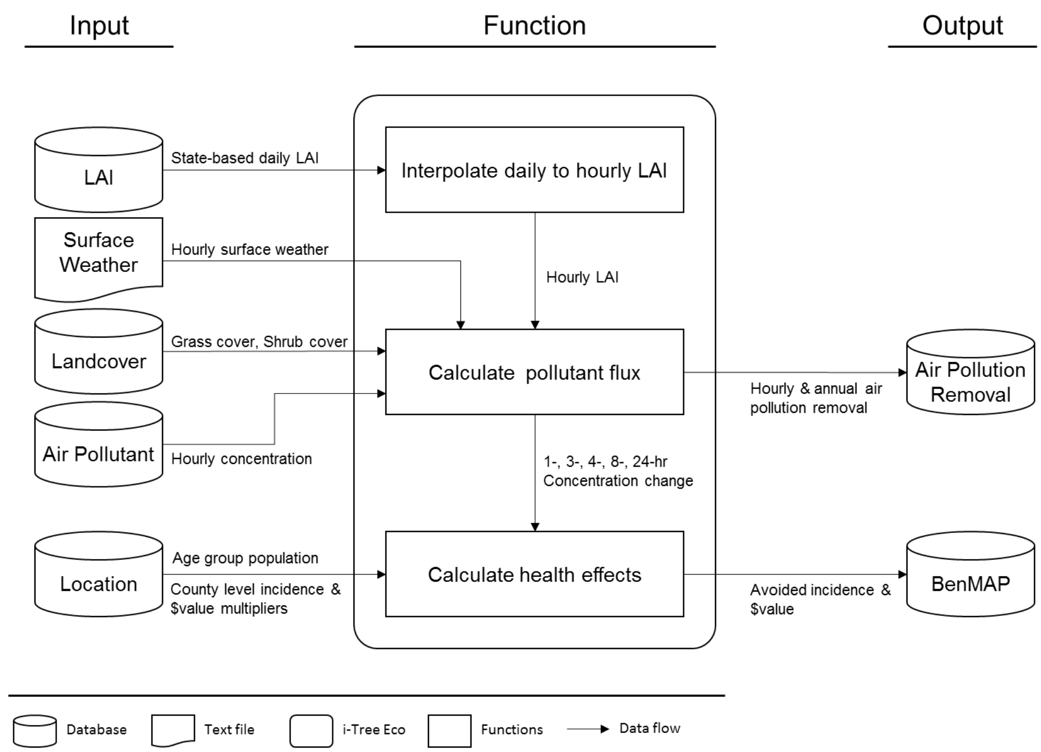

Figure 1: System architecture of i-Tree Eco, model inputs and outputs

For grasslands, as stomata exist on both sides of a leaf of a grass, the stomatal conductance used to calculate R_c was doubled. In addition, the number of vertical layers of vegetation which is used to estimate the solar radiation penetration through vegetation was set to 1 for grass as opposed to 30 for canopy and shrubs. Other parameters that were adjusted for grass includes rate of electron transport at 25 °C, and carboxylation rate of CO_2 between leaf and atmosphere.

Local hourly pollution concentration for different pollutants was obtained from the US EPA's Air Quality System database for 2010 (EPA) (2013b.)). The local hourly weather data was obtained from the National Climate Data Center for 2010 ((NCDC)). Further information on the pollutant removal by vegetation and change in pollutant concentration due to sequestration by vegetation can be found in Hirabayashi and Nowak (Hirabayashi and Nowak (2016)). Total annual pollutant removal by vegetation in each county was estimated as the product of annual flux ($gm^{-2}yr^{-1}$) and total vegetation cover (m^2).

2.3. Health incidence effects and monetary values of NO_2, O_3, $PM_{2.5}$ and SO_2 removal

Reduction in incidences of adverse health effects (morbidity and mortality) and the monetary value associated with pollutant removal by vegetation for NO_2, O_3, $PM_{2.5}$ and SO_2 were estimated using US EPA's BenMAP program. Adverse health effects include acute respiratory symptoms, emergency room visits, and hospital admissions from respiratory illness due to NO_2, O_3, $PM_{2.5}$, and SO_2, asthma exacerbations due to NO_2, $PM_{2.5}$, and SO_2, mortality due to O_3 and $PM_{2.5}$, school loss days due to O_3, and acute/chronic bronchitis, acute myocardial infarction, hospital admissions, cardiovascular, upper/lower respiratory symptoms, and work loss days due to $PM_{2.5}$. BenMAP uses spatially specific data to estimate health impacts and monetary value of air quality improvement to population (Davidson et al. (2007); Abt Associates (2010)). Based on BenMAP, i-Tree Eco has multipliers for adverse health incidences and values per unit change in air pollutant concentration per person in different age groups for each county in the conterminous United States. Vegetation effects on incidence and value for each health category were determined by multiplying the concentration change metrics (1-, 3-, 4-, 8- and 24-hour changes) due to air pollutant removal with a multiplier for each age group. Since the health effects have multiple functions corresponding to different concentration change metrics and age groups, multiple estimates for each health effect category were aggregated by either averaging or summing the estimates. Robust regression equations were then created to determine the relationship between population density and dollar value per tonne of pollutant removed by vegetation in rural and urban areas, as well as the county scale.

3. Results

Total annual pollution removal by grasslands and shrublands in the conterminous United States was estimated to be 3.36 million t (Table 1) and 3.06 million t (Table 2), respectively. The total human health value associated with pollutant removal was estimated to be $175 million for grasslands and $93 million for shrublands. These numbers are however lower than the benefits provided by trees and forests that are estimated to be 17.4 million t of pollutants with an associated human health value of $6.8 billion (Nowak et al. (2014)). Removal of air pollutants by grasslands was substantially higher in rural areas (3.33 million t) than urban areas (0.026 million t), while for shrublands, pollutant removal in rural areas was estimated to be 3.05 million t and 0.014 million t in urban areas. These numbers reflect the percentage of grassland and shrubland cover in rural and urban areas which varies from 0.07% to 12% in urban areas and 0.37% to 54% in rural areas for grasslands, while for shrublands the total cover ranges from 0% to 24% in urban areas and 0.04% to 79.5% in rural areas. At the national scale, total shrub cover in the lower 48 states ranged from 0.05% in Illinois to 79.2% for Nevada, and grass cover ranged from 0.4% in Vermont to 54.3% for Nebraska. The average daily LAI for grasslands was estimated to be 0.86, compared to 0.47 for shrublands as shown in Tables S1 and S2.

Table 1: Estimated removal of pollutants (tonnes*1000) and associated monetary value ($*1000) for grasslands in the conterminous United States

	Conterminous US		Urban		Rural	
Pollutant	Removal (t*1000)	Value ($*1000)	Removal (t*1000)	Value ($*1000)	Removal (t*1000)	Value ($*1000)
NO_2	298	2,270	2.69	1,540	295	726
O_3	2,870	111,000	21.70	60,300	2,840	51,070
$PM_{2.5}$	31.3	60,600	0.324	32,000	31	28,600
SO_2	162	360	1.21	194	161	166
Total	3,360	175,000	26	94,040	3,330	80,560

Table 2: Estimated removal of pollutants (tonnes*1000) and associated monetary value ($*1000) for shrublands in the conterminous United States

	Conterminous US		Urban		Rural	
Pollutant	Removal (t*1000)	Value ($*1000)	Removal (t*1000)	Value ($*1000)	Removal (t*1000)	Value ($*1000)
NO_2	382	1,780	2.11	1,240	380	542
O_3	2,520	65,200	11.8	34,700	2,510	30,400
$PM_{2.5}$	16.7	26,100	0.12	11,200	16.5	14,900
SO_2	140	190	0.64	89.6	139	100
Total	3,060	93,200	14.7	47,300	3,050	45,900

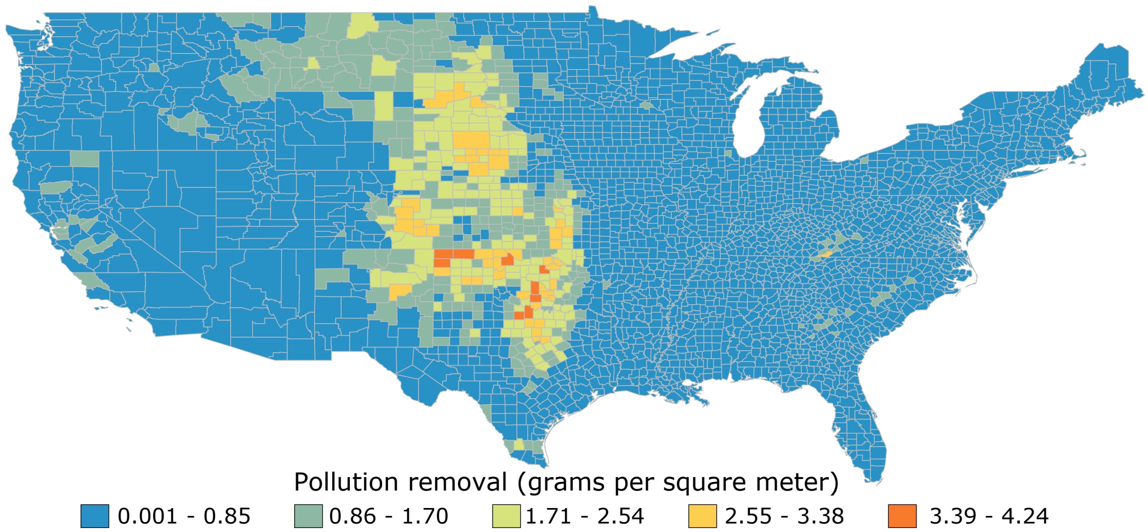

Figure 2: Estimated pollution removal (g m^{-2}) of all pollutants (NO_2, O_3, $PM_{2.5}$ and SO_2) by grasslands

However, the monetary value of pollution removal was observed to be moderately larger in urban areas than in rural areas. This value was estimated to be $80 million in rural areas and $94 million in urban areas for grasslands, and $47.3 million in urban areas and $45.9 million in rural areas for shrublands. This similarity in benefits for shrublands is due to the underestimation of the pollutant flux in the North East, Central and East North Central states, dominated by urban areas. Based on the available data, total biophysical benefits of shrublands were lower than grasslands which are lower than canopy cover. The greatest amount of pollution removal was for O_3 and NO_2, while the monetary benefits associated with removal of O_3 and $PM_{2.5}$ were significantly larger for both grasslands and shrublands.

Figures 2 and 3 represent the estimated pollution removal rate by grasslands and shrublands, respectively in different regions. States with the highest amount of pollutant removal include Texas, Montana, Nebraska and Oklahoma while for shrublands states with highest pollution removal include Texas, Arizona, Nevada, and California.

In terms of monetary benefits, highest benefits were observed in Texas, California, Oklahoma and Kansas for grasslands, and California, Florida, Texas and Alabama for shrublands. These monetary benefits are associated with reduction in health incidences mainly from asthma exacerbation (be-

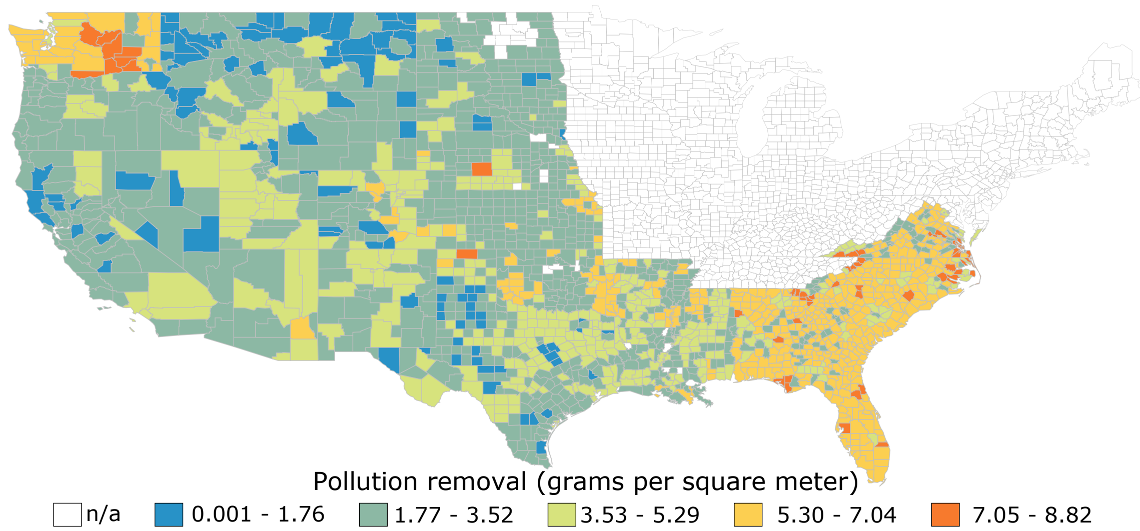

Figure 3: Estimated pollution removal (g m^{-2}) of all pollutants (NO_2, O_3, $PM_{2.5}$ and SO_2) by shrublands

tween 522 - 10,900 incidences for grasslands and 347 - 9,040 incidences for shrublands) and acute respiratory symptoms (between 56 - 14,500 incidences for grasslands and 37 -8,420 incidences for shrublands) as shown in Tables S3 and S4 in the supporting information.

Average removal rate of pollutant per square meter of grassland cover for all the pollutants varied from 2.85 gm^{-2} in rural areas to 3.5 gm^{-2} in urban areas, with an average national value of 2.85 gm^{-2}. For shrublands, pollutant sequestration per square meter of shrubland cover varied from 1.79 gm^{-2} in rural areas to 2.08 gm^{-2} in urban areas with an average value of 1.79 gm^{-2}. National average value associated with pollutant removal per hectare of grassland cover was estimated to be \$1.48, varying between \$0.69 in rural areas and \$127 in urban areas. For shrublands, average national value per hectare of shrubland cover was estimated to be \$0.545, varying between \$0.27 in rural areas to \$ 67.3 in urban areas. Nationally, percentage improvement in air quality is not high for grasslands and shrublands (Tables 3 and 4) but the maximum annual air quality improvement in some areas was high as 0.63 - 0.91% depending on the location. These trends were similar to the overall national air quality improvement provided by trees.

Table 3: Average annual values per tonne ($\$t^{-1}$) of removal and per hectare of grassland cover ($\$ha^{-1}$), average grams of removal per square meter of grassland cover (gm^{-2}) and average absolute and percent reduction in pollutant concentration in the conterminous United States

	Conterminous			Urban areas					Rural areas				
Pollutant	$\$t^{-1}$	$\$ha^{-1}$	gm^{-2}	$\$t^{-1}$	$\$ha^{-1}$	gm^{-2}	ΔC	$\%\Delta C$	$\$t^{-1}$	$\$ha^{-1}$	gm^{-2}	ΔC	$\%\Delta C$
NO_2	7.6	0.02	0.25	574	2.08	0.36	$1.00e^{-3}$	$1.60e^{-2}$	2.5	0.01	0.25	$3.00e^{-3}$	$4.30e^{-2}$
O_3	38.9	0.95	2.44	2,770	81.4	2.93	$7.00e^{-3}$	$2.30e^{-2}$	18.0	0.44	2.43	$2.20e^{-2}$	$7.20e^{-2}$
$PM_{2.5}$	1,940	0.52	0.03	98,600	43.2	0.04	0.00	$2.00e^{-3}$	923	0.24	0.03	$1.00e^{-3}$	$8.00e^{-3}$
SO_2	2.2	0.003	0.14	160	0.26	0.16	0.00	$2.40e^{-2}$	1.0	0.00	0.14	$1.00e^{-3}$	$7.60e^{-2}$
Total		1.48	2.85		127	3.5				0.69	2.85		

Table 4: Average annual values per tonne ($\$t^{-1}$) of removal and per hectare of shrubland cover ($\$ha^{-1}$), average grams of removal per square meter of shrubland cover (gm^{-2}) and average absolute and percent reduction in pollutant concentration in the conterminous United States

	Conterminous			Urban areas					Rural areas				
Pollutant	$\$t^{-1}$	$\$ha^{-1}$	gm^{-2}	$\$t^{-1}$	$\$ha^{-1}$	gm^{-2}	ΔC	$\%\Delta C$	$\$t^{-1}$	$\$ha^{-1}$	gm^{-2}	ΔC	$\%\Delta C$
NO_2	4.65	0.01	0.223	587	1.76	0.3	2.00e^{-3}	2.00e^{-2}	1.42	0.003	0.223	3.00e^{-3}	4.40e^{-2}
O_3	25.8	0.38	1.47	2950	49.4	1.68	7.00e^{-3}	2.10e^{-2}	12.1	0.178	1.47	1.80e^{-2}	5.60e^{-2}
$PM_{2.5}$	1,570	0.152	0.010	91,300	16	0.017	0.00	2.00e^{-3}	900	0.087	0.01	0.00	5.00e^{-3}
SO_2	1.36	0.001	0.082	140	0.127	0.091	0.00	2.40e^{-2}	0.72	0.000	0.082	1.00e^{-3}	6.10e^{-2}
Total		0.545	1.79		67.3	2.08				0.27	1.79		

Monetary values associated with reduction in adverse health effects were found to be highest for counties with a large population density. For grasslands, dollar values per tonne of pollutant removal was highest in New York county with a value of \$7,110 t^{-1} for NO_2, \$60,800 t^{-1} for O_3, \$3,660,000 t^{-1} for $PM_{2.5}$ and \$2,620 t^{-1} for SO_2. For shrublands, dollar values per tonne of pollutant removal was highest in San Francisco county in California with a value of \$2,670 t^{-1} for NO_2, \$23,600 t^{-1} for O_3, \$794,000 t^{-1} for $PM_{2.5}$ and \$1,050 t^{-1} for SO_2. As shown in Tables 3 and 4, the average value of pollutant removal was significantly higher in urban areas than in rural areas for grasslands and shrublands.

Regression equations estimating dollars per tonne of pollutant removed (y) with the population density (people per km^2, x) were estimated for rural and urban areas and at the county scale. For grasslands, county level regression equations for each pollutant were estimated to be

$$NO_2 : y = 0.6994 + 1.7024x \quad (R^2 = 0.85) \tag{3}$$

$$O_3 : y = 0.398 + 0.2425x \quad (R^2 = 0.78) \tag{4}$$

$$PM_{2.5} : y = 0.7621 + 0.0061x \quad (R^2 = 0.74) \tag{5}$$

$$SO_2 : y = 1.9583 + 4.1858x \quad (R^2 = 0.78) \tag{6}$$

For shrublands, county level regression equations were estimated to be

$$NO_2 : y = 0.44 + 0.4695x \quad (R^2 = 0.87) \tag{7}$$

$$O_3 : y = 4.64 + 3.2709x \quad (R^2 = 0.80) \tag{8}$$

$$PM_{2.5} : y = 164.6099 + 134.0709x \quad (R^2 = 0.77) \tag{9}$$

$$SO_2 : y = 0.2104 + 0.1571x \quad (R^2 = 0.78) \tag{10}$$

The mean R^2 for all regression equations are significant ($p<0.01$) and the coefficient of population density is significantly different from zero for all equations ($p<0.01$).

4. Discussion and Conclusions

Total annual pollution removal and associated human health values for grasslands and shrublands in the conterminous United States were found to be significantly high, with the pollution removal benefits exceeding that by trees and forests in many regions. Substantial fraction of pollutant removal takes place in rural lands ($> 99\%$) for both grasslands and shrublands. However, health and monetary benefits associated with pollutant removal were marginally higher in urban areas than in rural areas. In general, counties with a larger LAI and more land cover of grasses and shrubs had a higher amount of pollution removal, and the greatest monetary benefit from reduction in air pollution was observed in counties with the largest population density.

As mentioned in Nowak et al. (Nowak et al. (2014)), the main reason for the greater value of monetary benefits in urban areas than in rural areas is because BenMAP estimates benefits primarily on health impacts to humans. Thus monetary and health benefit numbers reported in this study are only conservative estimates since they include benefits only from four main criteria air pollutants and the monetary value associated with other benefits like recreational and aesthetic benefits are not included in this study.

Air pollution removal by grasslands and shrubland estimated in this study are all in the same domains (urban and rural areas in each county) as estimated for canopy by Nowak et al. (Nowak et al. (2014)), and these studies employ identical weather stations, radiosonde (upper air stations) and air pollution monitors, allowing a direct a comparison between the pollution removal rates by these different land classes. The primary difference between air pollution removal among the three vegetation classes stem mainly from the differences in LAI and land cover area for each vegetation class.

We observed that pollution removal by grasses exceeds pollution removal by canopy cover in four states in the Great Plains (Kansas, Nebraska, North Dakota and South Dakota). However, annual mean LAI of grasslands for these four states (0.48 - 0.60) was observed to be lower than the national average of 0.86. The higher removal rates in these regions are due to a larger land cover for grasslands (30-54%, Table S1) than trees (2.6% - 8%). For the rest of the states in the Great Plains including Colorado, Montana, New Mexico, Oklahoma and Wyoming, the total land cover area by grasslands were observed to be much higher than canopy, but the pollution removal rate by canopy cover was larger than grass. This is because, LAI for grasses for these states were very small (0.27 to 0.35 with an exception of 0.82 for Oklahoma), resulting in a lower pollution removal.

We observed that pollutant removal by shrubs exceeded that by canopy only in Nevada. This is due to a significantly larger shrub cover (79.2%) compared to canopy (11.6%), despite a very small LAI for shrubs. In other states like Arizona, Utah, and Wyoming pollutant removal by canopy cover and shrubland cover are comparable. These numbers provide an insight into the different benefits provided by grasslands and shrublands compared to canopy in different regions.

Pollutant removal by grasslands exceeded shrublands in several states including Colorado, Montana, Oklahoma and Virginia as shown in Tables S1 and S2. This is due to the greater grassland cover in most states except Virginia where the LAI for grasslands is larger. Despite comparable shrubland and grassland cover for the other states, LAI of grasslands was significantly larger than that of shrublands resulting in larger pollution removal capacity. Doubling the stomatal conductance of grasslands compared to shrublands also affected these results. These results can be observed by comparing Tables S1 and S2.

In terms of individual pollutant benefits, the greatest monetary and health benefits were observed for O_3 and $PM_{2.5}$. O_3 and $PM_{2.5}$ are the two main pollutant sources responsible for premature death and illness and $PM_{2.5}$ is also associated with other severe respiratory illness. Monetary benefits highly depend on the pollution concentration change (due to pollutant removal) and the population density (people/km^2). One main reason for the high pollutant removal value for O_3 is due to the high concentration of this pollutant in most counties and due to the high deposition velocity. Los Angeles County in California had the highest monetary benefits due to ozone sequestration by grasslands and shrublands, while Cook County in Illinois and San Diego county in California had the highest monetary benefits due to $PM_{2.5}$ sequestration by grasslands and shrublands, respectively. Monetary value of pollution removal by grasslands and shrublands were estimated to be high in several other counties in states like Arizona, Nevada and Florida due to reduction in mortality rate with change in pollutant concentration.

The total annual human health value for all 4 pollutants for grasslands was observed to be highest in Texas and California even though grassland cover is low. This is because, impacts on human health is larger in urban areas where vegetation is in close proximity to people than in rural regions. Monetary benefits of pollutant removal by grasslands were larger than canopy in North Dakota, while benefits were comparable in Nebraska and South Dakota, all in the great plains region. For shrublands, monetary benefits from improvement in human health was highest in states like California, Arizona, and Nevada which have the largest area of shrub cover ($>$ 40% of land area). Monetary benefits due to improvement in air quality by grasslands are higher than shrublands in 15 states including California, North Carolina and Virginia and benefits are comparable in South Carolina due to similar LAI values and percentage land cover of grasslands and shrublands.

In terms of the impact of removed pollutant mass on human health (Table 3 and Table 4), grasslands have a greater impact than shrublands. However, looking just at urban areas, these values were comparable among shrubs, and grasses, primarily due to a large population density in urban areas. For the four states in the Great Plains (Kansas, Nebraska, South Dakota and North Dakota) where high pollutant removal by grasslands occurred, population density in urban areas in these regions was close to the national average population density in urban areas. In addition, variation in urban population density is small across the country.

Impact on human health by grasslands and shrublands were much smaller in rural areas because population density is very low in these regions with much variability across the country. At the national level, pollutant removal by grass occurred mainly in the Great Plains area where the rural population density is much smaller (1.5 persons/km^2 in North Dakota to 3.5 persons/km^2 in Kansas) than national rural average (15 persons/km^2), resulting in a low contribution to human health benefits. These results indicate that shrublands and grasslands are equally critical in improving air quality and human health in urban areas.

Monetary values ($\$ha^{-1}$) and pollutant removal rate (gm^{-2}) estimated per unit vegetation cover area indicate the performance or effectivity of vegetation in removing air pollutants. Regardless of the vegetation type, the effectivity for O_3 removal was highest due to high concentration across the nation. Comparing grasslands and shrublands in the 26 states (Tables 3 and 4), shrublands are more effective than grasslands in removing pollutants mainly because of their larger LAI. This is because LAI is one of the primary factors that determine the pollution removal rates in vegetation (Hirabayashi et al. (2011)). Pollutant removal (gm^{-2}) for shrubs for urban areas could have been greater if the North East, Central and East North Central states dominated by urban areas had been included in the analyses, leading to a better performance for shrubs in the conterminous states.

Despite these limitations, this is the first study that provides insights on the sequestration capacity of grasslands and shrublands at the national scale. All the numbers reported in this study are based on the best available data at the county level and provide the most comprehensive estimates of pollution removal by grasslands and shrublands. This is also the first study that links the human health benefits and associated monetary benefit of grasslands and shrublands. These insights will encourage policy and decision makers to adopt effective land-use strategies that would aim at restoring ecological systems and maximizing these ecosystem services. Estimating the uncertainty associated with the i-Tree Eco model and parameter uncertainty associated with the LAI and meteorological data is a work in progress. i-Tree Eco estimates for canopy provide estimates for minimum and maximum deposition velocity from literature but such estimates are currently unavailable for grasslands and shrublands.

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