The Ecosystem service of forests improving air quality: A literature review

By

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ABSTRACT

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Air pollution regulation by forests helps to reduce the economic and human health impacts of damaging airborne particles. A variety of methods have been used to help study the economic impacts of forests regulating air quality. On average, forests improve air quality by up to 2%. But this improvement in air quality, when studied on a large scale, is millions of tons of air pollutants (including SO_2, NO_2, O_3, CO, and Particulate Matter under 10µm). These millions of tons of pollutants are worth billions of dollars in the United States alone. Urban forests have the most economic impact because of their proximity with humans, but on a larger scale rural forests uptake more pollutants. Finally, the use of mapping techniques to show study locations and present data enables the ability to quickly observe differences between locations within the same study, or differences between studies at the same location.

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1. INTRODUCTION

The concept of ecosystem services has become a widely accepted paradigm for valuing natural systems, including forests. The natural benefits – or services - of forests include watershed services such as erosion mitigation and regulation of baseflow; aesthetic and cultural services such as recreation; and climate or air quality services such as climate change mitigation through carbon capture and temperature regulation. Just over 30 years ago, President Ronald Reagan claimed that "trees cause more pollution than automobiles do", referring to the Volatile Organic Compounds (VOCs) that trees can give off in hot weather. Since then, the scientific evidence on how trees and forests affect air quality has grown, clearly showing that trees in fact improve the environment a great deal more than any combustion powered vehicle. In particular forests are capable of improving air quality by absorbing or trapping airborne pollutants which are harmful to human health. In this paper, I review the scientific literature on the ecosystem service of air purification provided by urban and rural forests in the U.S. (and contrasting this with values shown in example studies from other countries), synthesizing findings on how forests (or tree cover) affect concentrations of pollutants and how they affect human respiratory health, as well as studies that estimate monetary values for this ecosystem service. Through this review, I identify the sources of information and estimates that are most often used to estimate the volume and value of air pollutants removed by trees, and use the information given to summarize where studies have been conducted in the United States.

Air pollution has been shown to have a variety of negative health effects in humans including increased likelihood of respiratory disease and even premature death (Pope et al., 2009; Powe and Willis 2004). The Environmental Protection Agency lists a variety of pollutants that are harmful to humans, including Sulfur Dioxide (SO_2), Nitrogen Dioxide (NO_2), Ozone (O_3), Carbon Monoxide CO, and particulate matter smaller than 10μg (EPA, 2014). Trees and other plants absorb these gaseous pollutants through their stomata, and bind larger particles onto the surface of the leaf (Freer-Smith et al., 1997; Lohr & Pearson-Mims, 1996; Nowak et al., 2006; Przybysz at al., 2014; Terzaghi et al., 2013). This process is called dry deposition, as particles are removed from the air at a different rate during precipitation events.

In this paper, I review studies that quantify air pollution (excluding CO_2) uptake and the value of this service by forests in the US. The specific aims are to (1) identify and review the methods used for this quantification, (2) catalog the available estimates by different types of pollution, (3) and map the estimates based on location of data collection.

2. SYSTEMATIC REVIEW METHODS

The methods used for this review are listed in three subsections: 1) search strategy and study selection; 2) data extracted on the relationship between forests and air pollution; and 3) data extracted on the economic value of air pollution uptake by forests

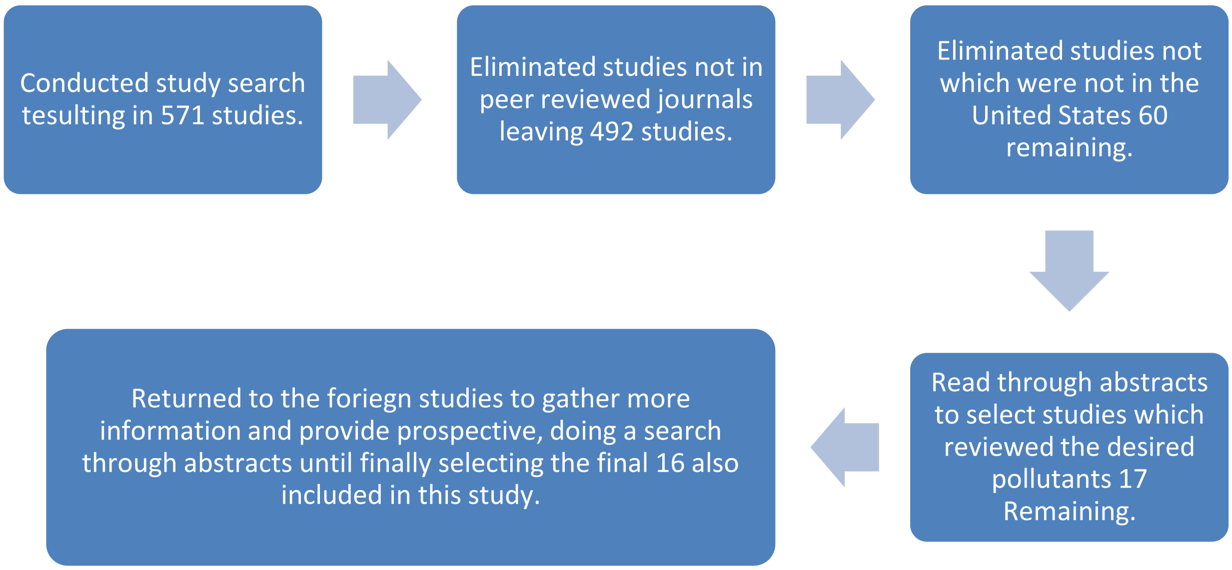
2.1 Literature Search

Published studies were identified through searches of the PROQUEST and EBSCO database managers, limited to publications in peer reviewed journals, after 1990, in English, and available through the NCSU library. I searched keywords, titles, and abstracts for key words. The search terms used to find studies were 'air pollution', 'air pollution removal', 'ecosystem services', 'tree', 'forest', 'pollution uptake', 'urban forest', and 'air quality'[1]. Abstracts for articles that came up in the searches were then read through and selected if they quantified either mitigation of air pollution by trees or the physiological effects on humans and plants from air pollution that is mitigated by trees. Selected studies were limited to those that quantified how plants affect air quality, with a focus on how trees remove pollutants from the air, the health effects from this on humans, pollution impacts on plant physiology with regard to its impact on pollution, and the value of improved air quality human health in monetary terms. Studies were limited to those published during or after 1990 in order to get the most modern interpretations of ecosystem services. The steps are shown in detail as well as the number of studies as they were narrowed down in figure 1.

To be included in this review, a study must have quantified some aspect of the relationship between air pollution, plant uptake, and human health. Only publications in English were included. All publications that met the criteria and were about the US were retained, international studies were selected because of their relevance to the topic, and to provide either background information, or to help provide an international perspective. Only peer reviewed published articles were included. Of those, only studies which included the pollutants listed by EPA (2014) as hazardous to human health (SO_2, NO_2, O_3, CO, and particulate matter) were included.

[1] The search pattern used searched in combinations of 3 terms all of which contained either 'air pollution' or 'air pollution removal' but not both, and contained 'tree' or 'forest' but not both due to the overlap of these search terms. E.g. 'air pollution OR air pollution uptake' AND 'forest OR Urban forest' AND 'air quality'. This was repeated with other terms in the place of 'air quality'.

Figure 1. A flowchart detailing the process of study selection.



In order to test the robustness of the original search, a repeat search was done on the database Web of Science using the same methods as those of the original search. The original search resulted in 571 possible results from the search terms, while the Web of Science search resulted in 496. After applying the same selection process to the web of science search only 11 studies were left in the U.S. that met the criteria. During the search many of the same U.S. studies were listed: Nowak et al. 2000, Nowak et al. 2013, Nowak et al. 2014, Rao et al 2014, and King et al. 2014; international studies included: Escobedo et al. 2009, Jim et al. 2008, and Setala et al. 2013.

3. RESULTS

Of the articles identified through the key word search of databases, 33 articles quantified either the ability of trees to remove air pollution from the atmosphere, or the value of air pollution removal by trees. These 33 studies considered five different pollutants, which are removed at different rates by trees (Table 1) and have different health effects on humans (Table 2). I reviewed the 33 studies, 17 of them located in the U.S., for evidence on these pollutants and extracted information on both the study methods and findings. Table 1 shows the number of published articles which estimated the dry deposition rate for each particular pollutant. Some studies involved analyses of multiple pollutants and therefore the studies listed in the table sum to more than 33.

Of the 17 studies conducted in the U.S., 14 estimated the value of improved air quality due to trees, whether by calculating the cost of alternative ways of removing pollution, or by calculating the value of reduced health problems in humans. Table 2 shows the potential health hazards of each air pollutant according to the EPA (2014). The values listed in table 2 are totals for the contiguous United States from Nowak (2006), which is referenced by 8 other sources (Campbell & Tilley, 2014; Cavanagh et al. , 2009; Dobbs et al., 2011; Escobedo & Nowak, 2009; Martin et al., 2012; Przybysz et al., 2014; Rao et al., 2014; Weber et al., 2014)

Table 1
Pollution rates in gram of pollution absorbed per square meter of green space per year (g/m^2/year), and the number of studies which gave rates for each pollutant

Pollutant	Range of Removal Rates (g/m^2/year)	Mean Removal Rate	Number of Studies
SO_2	0.2-2.73	1.05	8
NO_2	0.4-2.88	1.36	12

O_3	1.1-7.6	3.97	7
CO	0.1-0.57	0.305	5
PM	1.1-17.44	4.96	18

Mean removal rates are the mean of all values for each pollutant

3.1 Analysis of Study Content

The reviewed studies used different methods to quantify the amount of pollution removed by trees and the value of that contribution to air quality.

3.1.1 Difference in Uptake Measurement Method

Of the 33 studies, 9 used the Urban Forest Effects model (UFORE) to calculate values of dry deposition, and then multiplied that uptake rate by total green area and pollution concentration. The UFORE and i-trees methods are also applicable to rural forests despite the name (NRS, 2009). UFORE is data intensive in its requirements though as it takes standardized data from random field plots. So more recent studies have use the i-Tree program which combines the UFORE model and GIS technology to model pollution concentrations and uptake rates. Other models used in these studies were, median externalities valuation which is the analysis of median externality costs using statistical methods to calculate damages from pollution outputs on humans and the calculation of deposition rates based on deposition velocity calculations (Scott et al., 1998); and BenMap which used a combination of willingness to pay (WTP) information and healthcare costs to estimate the value in human health per ton of pollution(Nowak et al. 2014). Despite differences in the methodologies, and estimated all uptake rates fell within the ranges listed using the UFORE model.

All of these studies based their estimates on dry deposition rates, or the rate at which pollutants accumulate on surfaces in dry weather. Other deposition types include wet deposition which occurs during precipitation events, and occluded deposition, in which pollutants are captured by airborne water particles during fog events and deposited on surfaces. Dry deposition is a function of the deposition velocity, which is the reciprocal resistance to deposition by a particle (the sum of aerodynamic, boundary, and surface resistances of a particle), the leaf area index which is the amount of one sided leaf area per ground area, and the concentration of pollution at the given time (Janhäll, 2015). Pollution concentrations are often measured at specific times during the day, and averages per day are used to estimate deposition rates over an extended period of time.

Table 2. Human health effects of different pollutants, and their dollar value impact (cost to remove pollution at the source of emission) of their mitigation by all forests (urban and rural) in the contiguous United States in millions of dollars.

			Pollutant		
	CO	NO2	SO2	O3	PM
Human Health Effects	Chest pain	Inflammation	Increased respiratory illness, bronchoconstriction and increased asthma symptoms	Coughing and sore or scratchy throat	Premature death in people with heart or lung disease
	Reduced blood flow throughout the body	Worsened respiratory disease	Increased complications from respiratory illness particularly in children and the elderly	Inflamed and damaged airways	Nonfatal heart attacks
	-	Aggravated existing heart disease	Emphysema	Aggravated lung diseases such as asthma, emphysema, and chronic bronchitis	Irregular heartbeat
	-	Increased susceptibility to lung infection	Bronchitis	Increased the frequency of asthma attacks	Aggravated asthma
	-	-	-	Lungs are more susceptible to infection	Decreased lung function
	-	-	-	Continues to damage the lungs even when the symptoms have disappeared	Increased respiratory symptoms
Valuation of Removal for Contiguous US (Millions)*	22	660	117	2,060	969

*Values provided by Nowak et al. 2006

3.1.2 Differences in Ecosystem Service Valuation

Valuation methods differed based on the focus of each study. Studies with a greater focus on public input tended to use WTP. WTP uses stated preference of individuals, which is gathered via survey or interviews and uses that data to estimate values for specific costs. This method is useful in situations where the public feels it has an interest, policies are often shaped by WTP because of the public input, and policy makers often feel comfortable using them as a tool. But because it is survey based, is susceptible to the biases of individuals, which can lead to large variation in values, and unrealistic values for resources because survey takers do not believe that they will need to pay the cost themselves.

Avoided costs are the economic costs avoided by the existence of trees, e.g. the medical costs of treating respiratory which would otherwise be paid for in increased health problems. These studies used medical records and past emission levels to estimate the increase in medical complications from pollution levels, and then value the decrease in pollution based on the decrease in medical costs.

Rather than the benefits of trees, some studies estimate the abatement / mitigation cost, this is the economic cost of producing one unit less of pollution, rather than producing that unit and having it taken up by trees. This method may underestimate the cost imposed by pollution, but it does effectively represent the costs avoided by businesses due to pollution removal by trees. This method does not take into account the dispersion or concentrations of pollution, which makes it less useful for projecting costs in smaller regions.

Studies seeking to make accurate regional predictions of human health impacts tended to use BenMAP. The benefit of BenMAP is that because if focuses on the human health impacts of pollution, it is a valuable tool for measuring the improved quality of life that results from forests in a region. The shortcomings of this approach are that it fails to account for other damages or costs associated with air pollution and that it can be very data intensive, requiring a large number of field samples as well as input on tree species and GIS information. BENMAP can be described as a combination of WTP and avoided cost, which also uses GIS information and field samples to create highly accurate, localized, predictions. This also results in consistently lower values for pollutants because it ignores economic impacts of pollution such as the cost of reduced factory output to reduce pollution emissions and damages to natural resources. Some studies did not provide a value for pollution absorbed, and instead focused on the amount of uptake by trees, or the specific human health effects of air pollution concentrations. Table 3 lists the different valuation methods, their basic characteristics, and the studies that use each of them.

Table 3. Valuation methods, characteristics, and the studies they appear in.

Method	Characteristics	Studies
Abatement/marginal cost	Economic cost of producing one unit less of pollution which is instead taken up by plants	(Campbell & Tilley, 2014)(King et al., 2014)(Martin et al., 2012)(Nowak et al., 2006)
BENMAP	Combines GIS and Medical Information to establish damage reduction, then uses medical costs and WTP to establish final costs.	(Nowak et al., 2014) (Rao et al., 2014)
WTP	Survey Based	(Gómez-Baggethun & Barton, 2013)
Avoided Cost	Economic cost avoided by existence of trees, would otherwise be paid in medical costs or other impacts on human health	(Dockery et al., 1993) (Groot et al., 2002) (Wang et al., 2014) (Scott et al., 1998) (Nowak et al., 2013)

Did Not Assign a Value		(Grantz et al., 2003)(Lohr & Pearson-Mims, 1996)(Morani et al., 2011)(Nowak et al., 2000)(Pope et al., 2009)

Nowak et al. (2006) collected data from fifty five cities across the US. All other studies listed focused on single sites or limited regions, which makes it more difficult to apply their results to large regions. For this reason, Table 2 lists the values from Nowak et al. (2006). In other countries, Powe and Willis (2004) surveyed residents of the UK about avoided costs of hospital visits due to air pollution. Jim and Chen (2008) use official Chinese government values per ton of pollution to estimate the value of trees in Guangzhou China; these values are much lower than the values reported by other studies in table 6. This is because of the lower marginal cost of air pollution, caused by less sophisticated technology in air pollution costs, and lower labor and material costs (Jim & Chen, 2008). Because of the level of air pollution mitigation technology in use is relatively low, increasing emission standards is a lower cost than it would be in the U.S. which uses more sophisticated and expensive technologies. It is more expensive for a U.S. factory to update their air filtration system, than it is for a Chinese factory to put in a rudimentary one which meets their emission standards. Because of the limits of this lack of data variety, the Nowak et al. (2006) values are listed due to their aggregation of values for 55 U.S. cities.

Table 4. shows the set of studies in the U.S. identified in the literature review, as well as the pollutant considered by each one. Particulate matter was the most common pollutant studied, with 14 of the 17 studies measuring it. Studies in other countries are listed in Appendix 1.

Table 4. Pollutants covered by each study.

Study	SO2	NO2	O3	CO	PM
Campbell & Tilley 2014	X	X	X	X	X
Dockery et al. 1993					X
Gomez-Baggethun & Barton 2013	X	X	X	X	X
Grantz et al. 2003					X
Groot et al. 2002			X		
King et al. 2014		X			X
Lohr & Pearson-Mims1996					X
Martin et al. 2012	X	X	X	X	X
Morani et al. 2011	X	X		X	X
Nowak et al. 2000		X	X		
Nowak et al. 2006	X	X	X	X	X
Nowak et al. 2013					X
Nowak et al. 2014	X	X	X		X
Pope et al. 2009					X
Rao et al.2014		X			
Scott et al. 1998	X	X	X		X
Wang et al.2014	X	X		X	X

3.2 Impact of Air Quality on Human Health

The impact of air pollutants on human health has been well documented. Health effects in humans include reduced lifespan, increased occurrences of health problems, and lower quality of life. Particulate matter increased of mortality by 1.2% for all ages per 10 $\mu g/m^3$ according to Pope et al. (2009). They estimated that for every increase of 10 $\mu g/m^3$ of particulate matter, average life expectancy was reduced by 0.37 ±0.20 years, accounting for other variables like smoking and exercise habits. Greater tree density has been shown to reduce missed school and work days, emergency room visits, and reduced hospitalizations (Rao et al., 2014).

Because health effects and values derived from pollution removal are concentrated in urban areas, 68.1 percent of the value of pollution absorption occurs in urban areas despite being a significantly smaller portion of overall forest cover in the U.S.(Nowak et al., 2014). This difference in value is caused by urban forest areas having a higher impact on human health than rural forests (Nowaket al. 2014). BenMAP simulations estimate the overall health impacts of pollutants on human health, using a combination of cost of illness and willingness to pay metrics, to generate values for air pollution. These simulations tend to have a greater range of values but a lower value per ton of pollution. Using median air pollution costs from Europe which include health costs, crop losses, and damage to buildings, the value of pollution removal by trees in the U.S. increases from $6.8 Billion (with a range of $1.5-13 Billion) to $86 billion (Nowak et al., 2014)

In Portland Oregon, Rao et al. (2014) used BenMAP to estimate that the reduction of NO_2 by urban trees resulted in approximately 21,000 fewer incidences of asthma exacerbation for 4-12 year olds, 54 fewer emergency room visits across all age groups, and 46 fewer cases of hospitalization due to respiratory problems in the elderly. These reductions were valued at $7 million.

4. EFFECTS OF FORESTS ON AIR QUALITY

Plants, through dry deposition are able to uptake air pollutants which results in cleaner air and reduced health complications. The rate of dry deposition varies based on a variety of factors. The volume of green space in an area, as well as the density of pollution in the air impacts the velocity of dry deposition. Trees have the highest rate of deposition of pollutants of any land cover type (McDonald et al., 2007). However, the layout of the forest can have a large impact on deposition rates. If trees are positioned in such a way that they block airflow, they can increase the local concentration of air pollution beyond what it would be if winds were able to disperse it more evenly (Morani et al., 2011).

Dry deposition rates are estimated based on the hourly concentration of pollution, the forest area, forest type, leaf area index, and particle size (Bowler et al., 2010; Escobedo & Nowak, 2009; McDonald et al., 2007). Differences between these variables result in different uptake rates (Table 5), and in different levels of pollution removal for each region studied (Cavanagh, et al., 2009; Escobedo & Nowak, 2009; Freer-Smith et al., 1997; Gómez-Baggethun & Barton, 2013; Nowak et al., 2006, 2014; Przybysz et al., 2014; Setälä et al., 2012; Terzaghi et al., 2013).

Because uptake is dependent on pollution density and available green space, the relationships between these variables are not linear (Currie & Bass, 2008): more green space does not mean the maximum amount of pollution will be absorbed. Forests along traffic corridors can limit wind flow, which causes higher deposition rates to the plants directly next to the source of the pollution. Adding more trees further away will not necessarily have the same impact as planting more further along the same traffic source.(Currie & Bass, 2008; Escobedo & Nowak, 2009; Morani, Nowak et al., 2011; Weber et al., 2014). The UFORE model, used by many studies to determine overall levels of pollution, suggests that trees remove less than 2% of air pollution in urban environments, and roughly 10% in more rural locations where canopy cover approaches 100%, but this would likely only be a temporary rise in uptake. Eventually pollution levels would lower and air quality would improve due to reduced pollution output, leading to uptake rates returning to less than 2% (Nowak et al,. 2006; Setälä et al. 2012). Because the density of pollution would have fallen and the volume of green space increased, uptake rates for the area would be lower on a per meter basis.

Table 5. Cited studies, including sampling methods, study area, total uptake in tons, and uptake per pollutant in g/m^2/year

Study	Sampling Method	Study Area	Total Uptake For Study Area (Metric Ton)	NO2		O3		CO		SO2		Particulate Matter	
				(g/m^2/year)	(%)	(g/m^2/year)	(%)	(g/m^2/year)	(%)	(g/m^2/year)	(%)	(g/m^2/year)	(%)
Campbell 2014	UFORE	Maryland	32,400	0.74		1.74		0.15		0.41		0.82	
King 2004	UFORE / i-Tree	New York, New York	NA	3.33		NA		NA		NA		1.59	
Nowak 2006	EPA Monitoring	Urban Centers USA	711,000	0.40-2.88	0.1-0.5	1.10-7.60	0.1-0.8	0.10-0.57	.001-.003	0.20-2.73	0.10-0.70	1.1-17.3	0.2-1.4
Nowak 2014 (Urban)	EPA Monitoring	Conterminous USA	650,000	0.70	0.23	5.40	0.36	NA		0.34	0.34	0.27	0.13
Nowak 2014 (Rural)	EPA Monitoring	Conterminous USA	16,719,000	0.55	0.27	5.49	0.51	NA		0.35	0.48	0.27	0.20
Scott 1998	Manual Sampling	Sacramento California	1,457	NA		NA		NA		NA		NA	

The uptake ability by trees also varies by season. While particulate matter is captured by being deposited on the leaf or plant surface, all other pollutants require transpiration to become trapped in the mesophyl of leaves (Nowak et al., 2006, Terzaghi et al. 2013). This means that during the night and winter most forests are only capturing particulate matter (PM) and no other pollutant. Even the rate of capture of PM is reduced given that part of the rate of dry deposition is based on the leaf area index of a given space. Conifers and evergreens are able to maintain PM absorption rates year round, but are subject to higher than average leaf mortality because they do not drop their entire leaf stock each year. This can cause a buildup of potentially damaging particles on the surface of the plant, which will kill leaves and needles earlier and reduce future uptake potential.

High levels of air pollution also have a negative effect on plant health as well. High concentrations of particulate matter can reduce photosynthesis and damage leaf tissues, inducing a premature leaf fall (Grantz et al., 2003).This increase in damage leads to reduced biomass, and in some areas normally dominant species have failed to develop. This leads to an altered species composition, which often has a thinner density than a health stand (Grantz et al., 2003). This stress also reduces the ability of trees to fight disease or pests, which can increase management costs, and decrease overall forest efficacy in removing pollution. If a city had a monoculture of trees for their urban forests, reduced ability to combat pests may cause a large die off, and greatly reduce the uptake of pollution.

Because of the variety of factors affecting the velocity of deposition, deposition rates are variable for each area studied. The most common method for calculating total pollution removal was the UFORE model of pollution concentration measurement. This model takes into account forest species composition, diameter distribution, tree health, species diversity, and calculates forest functions and values related to air pollution, greenhouse gasses, and building warming energy to establish a baseline of deposition velocity for the surrounding area(NRS Webpage). The biggest problem with UFORE is that it the data requirements shown are very large and can be difficult to completely catalog even with the i-tree tools, including GIS information and forest species composition. The benefit of i-tree is that it streamlines geographic data requirements, reducing the amount of required information required to create an accurate map of pollution distribution by allowing data like species composition, forest type and wind buffer information to be supplied by GIS shapefiles and databases instead of manually recording the information. In order to simplify the presentation of the pollution uptake data, all of the studies listed in tables 3 and 4 have had their uptake rates per unit of land area converted to uptake volume per square meter of green space per year if the study listed a unit per area rate of pollution uptake.

One effect of trees that does not benefit human health is the creation of Volatile Organic Compounds (VOCs). VOCs are produced by trees and can contribute to the formation of O_3 and PM at the 2.5µg size level. These emissions are both temperature and species dependent (Escobedo & Nowak, 2009; Nowak et al., 2014; Setälä et al., 2012). Research into how these affect air pollution concentrations is ongoing. It is still unclear if trees in urban environments produce a net positive or negative amount of these pollutants given that they both produce and uptake them (Escobedo & Nowak, 2009).

The deposition of atmospheric nitrogen and particulate matter is an important environmental factor for plants. Atmospheric disposition supplements nutrient input in soils that is lost by uptake to plants. Many forest systems are normally nitrogen deficient, and this atmospheric deposition alters the normal relationship in many forest ecosystems, in which species must compete for scarce nutrients. Species that normally struggle to compete in nitrogen poor environments are able to gain a competitive advantage because of deposition from manmade pollution. However over saturation of nitrogen can also lead to a decline in forest productivity and increased plant mortality which reduces the long term economic benefits of using plants as pollution sinks (Grantz et al., 2003; Morani et al., 2011).

A buildup of particulate matter on the surface of leaves can negatively affect plant health in a variety of ways. Inert particles can build a crust which reduces the photosynthetic capabilities of the plant. Alkaline particles in contrast can directly injure the surface tissue of plants and reduce the survivability of saplings. These damaging particles eventually lead to a less dense forest which is less efficient at capturing pollution (Grantz et al., 2003; Morani et al., 2011).

5. VALUATION OF FORESTS

For many studies the values of pollution per volume (usually metric ton) were based on estimated government costs of abatement per ton. Older models used a Best Available Control Cost Technology cost analysis (Scott et al. 1998) which was limited in estimating the effectiveness of trees, by the knowledge of the deposition rates during that time (Nowak et al., 2000). Nowak suggests that the findings of Scott et al. (1998) are debatable as they omitted the quantification of the net effect of urban trees on air quality. The values listed per pollutant per metric ton from Nowak et al. (2006), are: SO_2 = \$1653, NO_2 = \$6752, O_3 = \$6752, CO = 959, PM

= 4508, and these values are those most commonly used by other studies. Another study (Jim & Chen, 2008) used a marginal cost method for the valuation of pollutant removal, which means that the additional cost of abating one unit of air pollutant was the cost of removal. Values for this study were taken from the State Environmental Protection Administration of China and the values are much lower than those used by all non-Chinese papers. The values for these pollutants in Jim& Chang (2008) are: SO_2 = \$72, NO_2 = \$72, and PM = \$22. These values for tons of pollution were then multiplied by the estimated amount of pollution uptake occurring based on standard rates for dry deposition.

From an economic perspective, protected forests may be cheaper methods of pollution mitigation than managed forests because they do not require a consistent input of funds to manage them. However, Martin et al. (2012) estimated that managed forests to have a greater rate of absorption ($\$5.5 \times 10^{-2}/m^2$/year) compared to protected forests with minimal tree management ($\$6.7 \times 10^{-3}/m^2$/year) based on their observations. These data were collected using i-tree analysis comparing protected and managed areas on Auburn University's campus (Martin et al. 2012).

Table 6. Values and Valuation Methods of Studies in Dollar value per square meter of green space per year ($\$/m^2/year$)

Study	Valuation Method	Study Area	Total $ Value of Study Area (Millions per Year)	No2	O3	Co	So2	pm
Campbell 2014	Abatement Cost	Maryland	167	0.0074*	0.01744*	0.0015*	0.0042*	0.0082*
Nowak 2006	Abatement Cost	55 U.S. Cities	3,800	0.0074	0.01744	0.0015	0.0042	0.0082
Nowak 2013	Avoided Cost	10 Major U.S. Cities	15,426	NA	NA	NA	NA	0.162
Nowak 2014 (Urban)	BENMAP	Conterminou s USA	4,658.4	0.000305	0.015476	NA	0.000051	0.032314
Nowak 2014 (Rural)	BENMAP	Conterminou s USA	2,184.9	0.000004	0.000287	NA	0.000001	0.000578
Rao 2014	BENMAP	Portland, Oregon	6.59	NA	NA	NA	NA	NA
Scott 1998	Avoided Costs	Sacramento, California	28.7	NA	NA	NA	NA	NA

*Values based on those used in Nowak et al. 2006

The difference between rural and urban valuation have not been extensively studied. Nowak et al. (2014) and Rao et al. (2014) are the only papers to thoroughly study this difference. The total volume of pollution absorbed by trees in rural environments far exceeds that of urban trees, 16.7 million tons for rural environments compared to 650 thousand tons for urban (Nowak et al., 2014). However, the corresponding values for each show the importance that the method of valuation can have. Because the BENMAP valuation method focuses on the human health benefits of reduced air pollution relies on medical data for valuation, pollution in regions with a higher population density is more highly valued, resulting in urban pollution removal being valued at $4.6 billion, while the value of rural pollution removal is only $2.1 billion despite absorbing 25 times more pollution. Regression equations to estimate dollars per ton in Nowak (2014) revolved around the population density per km^2. This caused a difference in the average per hectare value of tree cover, $9 for rural areas and $481 in urban ones. As shown in table 6, the value of the pollution taken up by a square meter of green space in an urban environment is many times the value of equivalent pollution removal in a rural environment.

Pollution that is widely dispersed in rural environments impacts fewer individuals, which reduces the value of rural green space from a purely human health perspective. This also corresponds with the concept that cities with more tree cover will value each unit of pollution at a lower cost because there will be less of it in the air, which results in a diminishing marginal benefit from tree cover.

An interesting contrast appears when comparing the established values in table 6 between the Chinese government in Jim and Chen (2008) compared to the values from Nowak et al. (2006). Both of these values take in to consideration health human impacts, agricultural damages, and environmental damages, but for economic, cultural, or political reasons the values given by the Chinese government are significantly lower than even the urban values given by Nowak et al. (2014). The increased presence of the UFORE model of pollution concentration in recent studies has shown a consistent trend toward using the i-trees technology to establish pollution concentrations and absorption rates. However the focus of the UFORE method is the cost of removal of a ton of pollution with value given based on a variety of damages that the pollutant can cause. The BenMAP model focused on health impacts of pollution on human health, and because it lacked other inputs of damage, gave a lower value per ton of pollution than studies using the other pollutant costs.

Studies tended to focus on green space as a whole, or to focus primarily on deciduous trees due to those being the more common tree in urban environments. But conifer and evergreen planting may actually be preferable to deciduous tree when PM concentrations are at very high levels. These plants have a more waxy cuticle and airborne pollutants are more likely to adhere tightly to the surface(Jim & Chen, 2008; Przybysz et al., 2014). The benefits of conifers and evergreens are even more apparent in winter when PM concentrations are often at their highest, and deciduous trees lack the leaf area which is key to dry deposition. However conifers are also more susceptible to physiological damage from this deposition than their deciduous counterparts. The cause for this has not been studied in depth yet but it is possible that sensitivity to heavy metals may have a negative effect on needle health, reducing the health and capabilities of the trees(Jim & Chen, 2008; Przybysz et al., 2014; Richardson et al. 2015). Przybysz et al. (2014) suggests that conifers could provide the maximum benefit, not by being planted in areas with high maximum pollution, but in areas with consistent rates of moderately high pollution year round, where they can assist in uptake without suffering too much stress.

6. MAPPING STUDY LOCATIONS

The mapping portion of this project (https://www.google.com/maps/d/u/0/edit?mid=zXrM8kdwOeTc.k0x-P5qqGd9w) involved finding studies which listed their sampling locations as an area no larger than a major city in the United States and gave values for uptake rates of pollutants. Of the 17 U.S. studies originally used in this project only twelve met the criteria. Some studies could not be mapped because their sampling information could not be found or narrowed down to a specific enough location to plot on Google Maps. For example, Campbell et al. (2014) calculate pollution deposition rates for the entire state of Maryland, and unfortunately the link providing for information on their sampling sites no longer works.

The custom Google map displays the sites color coded by article as shown in figure 2. Studies are organized by color, with each color representing a different study. Some pins are hidden at a larger scale due to their proximity to other pins, but by hovering the mouse over a study name, each site listed for that study is highlighted and made visible. Studies for a wider area than a single city are represented by stars, while more localized studies are represented by rounded pins as shown in figure 2. Nowak et al. 2014 is listed as a separate map layer because it presents data differently than other studies. Instead of listing each pollutant as shown in Figure

4, for each state it shows pollution uptake in rural and urban areas, the percent of the state that is classified as urban, and the percent of the state classified as forest.

The benefit of the map is that it makes it easier to visualize amount of forested area in a city, as Google maps will highlight metropolitan areas, and it becomes easier to conceptualize factors like aridity of a region an impact of the percent forest cover. Regions like Arizona have a high amount of arid land which means that even though it is not highly urbanized, it does not have a high rate of uptake compared to other states. The District of Columbia in Nowak et al. 2014 is the only area listed as being 100% urban, and therefore having no area designated as forested.

Figure 2. The map of all sampling locations from the selected study

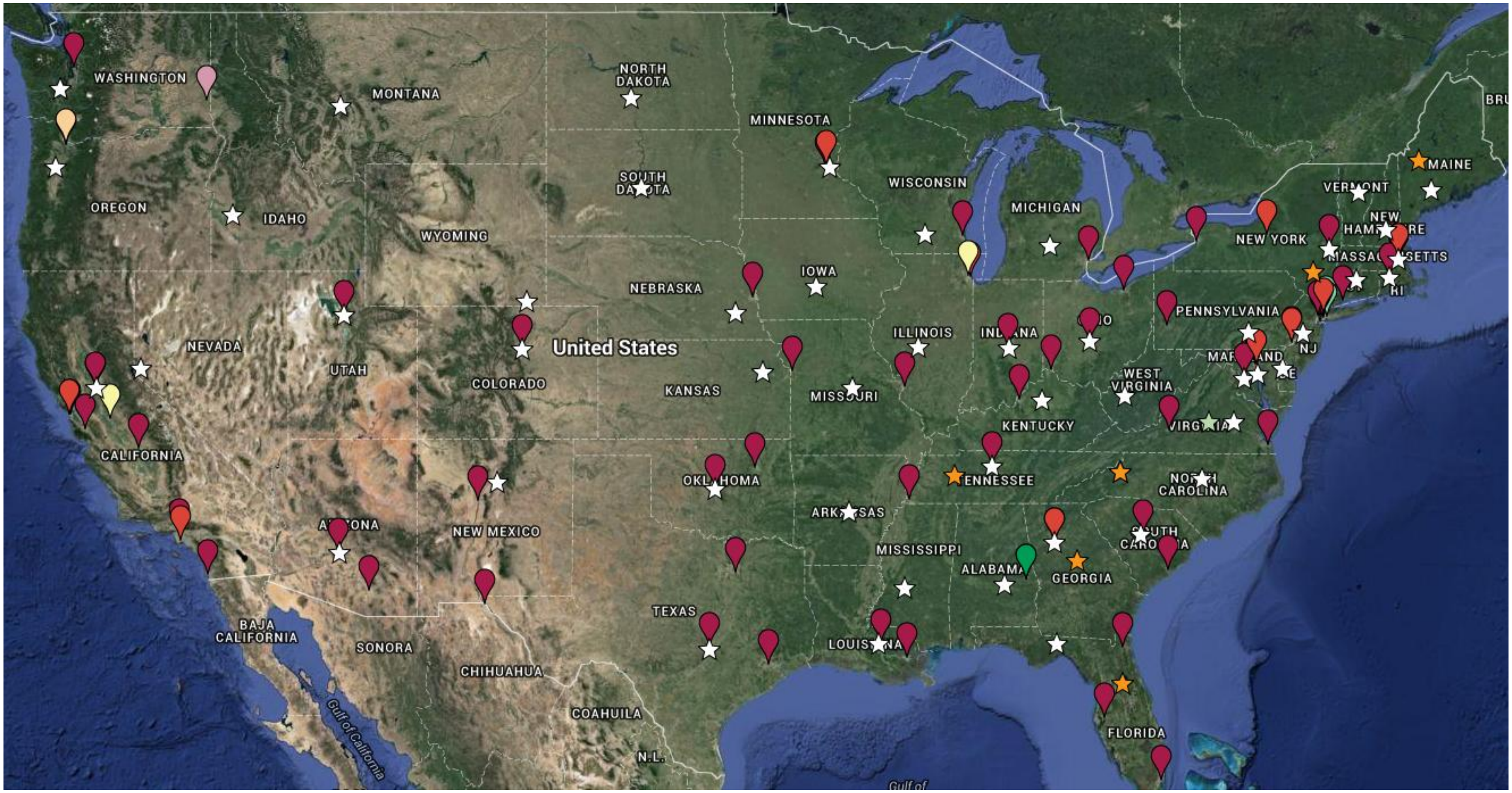


Figure 3. The listed information for each pin

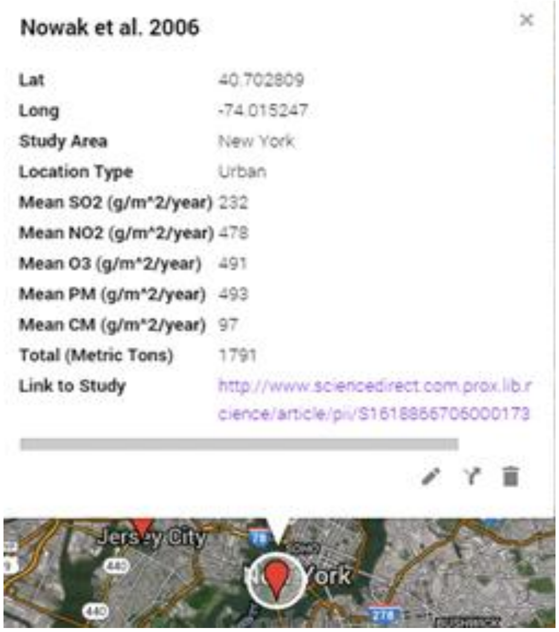
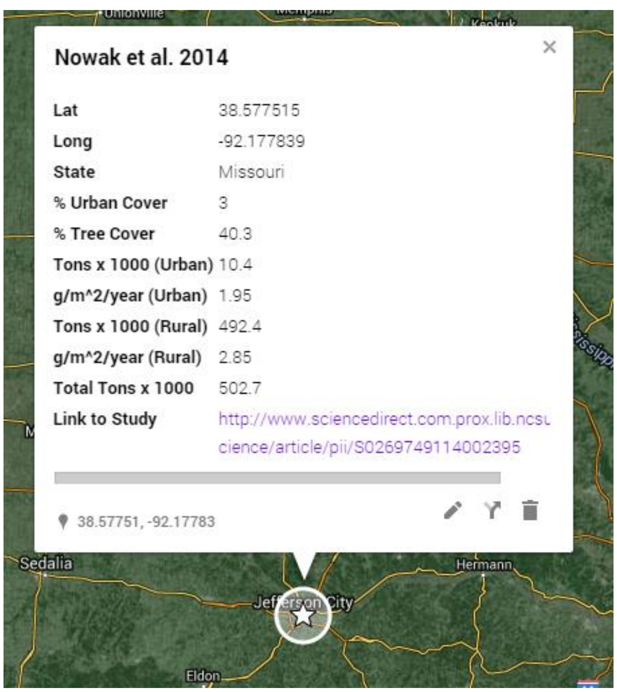


Figure 4. Information from a pin in Nowak et al. 2014



Of the 17 studies in the United States, the five that could not be mapped were Dockery et al. 1993, Groot et al. 2002, Morani et al. 2011, Pope et al. 2009, and Wang et al. 2014. They were either medically focused and recorded ppb rates, or were economically focused and used data from other studies to calculate economic values for pollutants. Because these studies did not measure pollution rates in particular sites, it did not make sense to map them.

7. DISCUSSION AND CONCLUSIONS

The UFORE model of pollution removal shows less than 2% of air pollutants are removed by trees, which has led some to question the validity of using trees as a pollution sink. But given the wide variety of health benefits that even moderate tree cover is able to provide, it seems a mistake to judge their benefits based only on the percentage of pollutants removed.

Trees as an air scrubber in urban planning may have limited effectiveness, but in conjunction with tighter regulations on air pollution, plants might be able to effectively act as sinks in areas that experience high rates pollution from traffic. Unfortunately tree mortality has a sizeable impact on the effectiveness of this strategy. For example, increasing annual tree mortality from 4% to 8% would reduce the total volume of pollution removed over 100 years by over 60% (Morani et al., 2011). This does not suggest that trees be abandoned as a strategy for pollution capture, but rather that careful attention should be paid to species selection and management for proposed mass planting where trees will be stressed by high pollution levels.

One potential area for future study is particulate matter at the 2.5μg in size. This size category is only studied in depth in articles after 2008. Nowak et al. (2013) estimates that the reduction to mortality due to $PM_{2.5}$ uptake by trees in U.S. cities is typically 1 person per year per city, but is as high as 7.6 people per year in New York City. As cities continue to grow, the impact of $PM_{2.5}$ on human health will become more pronounced. Increased planting of evergreen and coniferous trees appears to have the greatest impact on $PM_{2.5}$ absorption compared to other pollutants.

In conclusion, forests, both urban and rural, provide a variety of ecosystem services. With regards to air pollution, forests are a viable source of pollution capture to improve air quality and thereby improve the health and quality of life for the people that live near them. The literature review in this paper demonstrates the need for more research to support valuation of forests not just for their timber or carbon sequestration, but for the wide array of other services that they provide.

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Appendix 1. Studies outside the US.

Authors	Country	Pollutants studied
Bealey et al., 2006	UK	PM10
Beckett et al., 1998	England	PM10
Brack, 2002	Australia	NO2
Cavanagh et al., 2009	New Zealand	PM10
Currie & Bass, 2008	Canada	SO,NO2,O3,CO,PM
Escobedo & Nowak, 2009	Chile	SO,NO2,O3,CO,PM
Freer-Smith et al., 1997	England	PM10
Janhall, 2015	Sweden	PM10
Jim & Chen, 2008	China	SO2, NO2, PM
Kampa & Castanas, 2008	Greece	SO2,NO2,O3,CO,PM
Mcdonald et al., 2007	UK	PM10
Powe & Willis, 2004	UK	SO2,PM
Przybysz et al., 2014	Norway	PM10
Setala et al., 2012	Finland	NO2

Terzaghi et al., 2013	Italy	O3
Weber et al., 2014	Germany	PM

Table 5b. International studies

Escobedo 2009	UFORE / i-Tree	Santiago, Chile	931	1.2	1.35	2.47	2.23	0.40	0.02	0.6	1.60	7.45	5.40
Jim 2008	Manual Sampling	Guangzhou, China	NA	2.64		NA		NA		2.73		10.9	

Table 6b. International Studies

Brack 2002	Marginal Cost	Canberra, Australia	1.05	NA	NA	NA	NA	NA
Jim 2008	Marginal Cost	Guangzhou, China	0.009	0.000081	NA	NA	0.000081	0.000081
Powe 2004	WTP	Britain	1.395	NA	NA	NA	NA	NA