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Urban natural capital accounts: developing a novel approach to quantify air pollution removal by vegetation

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ABSTRACT
Air pollution presents a major risk to human health, resulting in premature deaths and reduced quality of life. Quantifying the role of vegetation in reducing air pollution concentrations is an important contribution to urban natural capital accounting. However, most current methods to calculate pollution removal are static, and do not represent atmospheric transport of pollutants, or interactions among pollutants and meteorology. An additional challenge is defining urban extent in a way that captures the green and blue infrastructure providing the service in a consistent way. We developed a refined urban morphology layer which incorporates urban green and blue space. We then applied an atmospheric chemistry transport model (EMEP4UK) to calculate pollutant removal by urban natural capital for pollutants including $PM_{2.5}$, NO_2, SO_2, O_3. We calculated health benefits directly from the change in pollutant concentrations (i.e. exposure) rather than from tonnes of pollutant removed. Urban natural capital across Britain removes 28,700 tonnes of $PM_{2.5}$, NO_2, SO_2, O_3. The economic value of the health benefits are substantial: £136 million in 2015, resulting from 900 fewer respiratory hospital admissions, 220 fewer cardiovascular hospital admissions, 240 fewer deaths and 3600 fewer Life Years Lost.

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1. Introduction

Air pollution is a major cause of death and contributes to the burden of non-communicable diseases globally (Lim et al. 2012), particularly in high population density megacities and countries experiencing rapid industrial expansion (Liu et al. 2017). The health impacts include respiratory illness, cardio-vascular complications, a loss of life expectancy and premature deaths. Air pollution is rarely the sole cause of death but often exacerbates existing health conditions. Nonetheless it poses a serious health risk, with considerable cost to society (Cohen et al. 2005).

The principal pollutants which give rise to these health impacts are particulate matter, oxides of nitrogen and sulphur, ammonia and ozone (WHO 2006, 2013). Particulate matter (PM) includes particles of different size fractions, from a range of primary and secondary sources. Most health impacts of particulate matter are attributed to fine particles with a diameter less than 2.5 microns

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($PM_{2.5}$), which are small enough to travel deep into the lungs. Ammonia is primarily generated in rural areas from agriculture sources, but is transported to urban areas by atmospheric transport and in its aerosol form can be a substantial component of secondary $PM_{2.5}$ material. Nitrogen oxides (NO and NO_2) come primarily from combustion sources like power stations and vehicle exhausts and cause increased likelihood of respiratory problems. Sulphur dioxide (SO_2) is an irritant to mucous membranes and can exacerbate health conditions like asthma. Ozone (O_3) is a secondary pollutant formed by photochemical reactions with other pollutants. It is a powerful oxidant, causing damage to lung tissue and is a cause of premature deaths.

Plants are able to remove air pollutants from the atmosphere. They do this through two principal mechanisms. The first involves direct deposition of particulate and gaseous pollutants onto leaf and stem surfaces. The second involves uptake of particles and gases into the plant through stomatal leaf openings which the plant uses for photosynthesis and respiration. Collectively this process is called dry deposition, and is distinct from wet deposition which occurs when particles and gases are washed out of the air during rainfall.

A developing literature is quantifying and valuing the amount of 'pollutant removal' service provided by vegetation. Studies in the USA have shown substantial economic benefit from pollution removal by vegetation across US cities (Nowak, Crane, and Stevens 2006; Nowak et al. 2013; Nowak et al. 2014). In the UK PM_{10} removal by vegetation in part of London was modelled using an integrated modelling approach (Tiwary et al. 2009), and in China Yang et al. (2005) modelled pollution removal by urban forest in Beijing. However, there is some controversy over the real magnitude of benefit provided (Setälä et al. 2013; Whitlow et al. 2014), with typical reductions in pollutant concentrations only around 1%. This may in part be due to limitations in the methodologies applied to calculate the quantity of pollution removed. These include (i) A spatial disconnect between where pollution is removed by vegetation, and where those benefits are realised, which is a classic ecosystem services problem. The majority of approaches used to calculate pollutant removal are static, i.e. they assume that the benefit can only be quantified within the area where the pollutants are removed. In this way rural areas which have high vegetation cover but low populations are deemed to have low value, while the vegetation in urban areas with a large benefitting population is attributed a high value, even if it has relatively low vegetation cover. In reality, as illustrated in Figure 1, pollution moves with atmospheric transport processes, and therefore so does the benefit of lower pollutant concentrations as a result of pollution removal by vegetation. A related issue with most static approaches is that pollutant removal is calculated in isolation for each pollutant, while in reality, chemical interactions among pollutants in the atmosphere mean that the eventual deposition velocities for one pollutant may be dependent on concentrations of another pollutant. Lastly, while static approaches often take into account some meteorological factors such as number of rain days and broad seasonality trends of leaf-on periods for deciduous species (e.g. Powe and Willis 2004), they often do not account for other factors such as wind speed which is a major determinant of deposition velocity for many pollutants.

In tandem with the emerging literature on pollutant removal, there is growing interest in developing natural capital accounts for ecosystem services (e.g. Chen et al. 2018). These aim to report on the economic benefits of natural capital at national level, and which are compatible with international initiatives such as the System for Environmental Economic Accounts. Natural capital in this context is the vegetation which provides the service of pollution removal, which can include trees but also other forms of vegetation such as grassland, moorland and even croplands. There is also interest at the city or municipality level in the potential to manage primarily urban vegetation as a means of mitigating local pollution concentrations. Many approaches for quantifying services at national scale for natural capital accounting are relatively unsophisticated, relying on matrices of service delivery against land cover/land use classes or data from existing indicators (Maes et al. 2013). Such approaches rarely take account of spatial context which is critical in assessing most ecosystem services (Eigenbrod et al. 2010). This gives added impetus to improving the methodologies used to calculate health benefits, so that they realistically estimate the amount of pollution removed by vegetation, and the resulting health benefits arising from that.

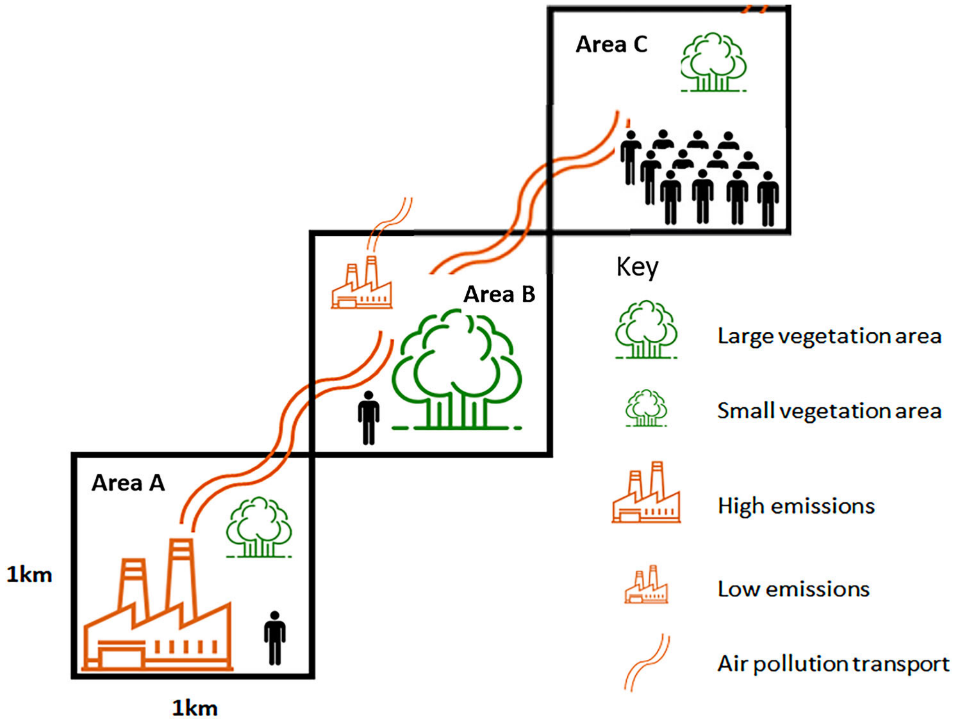

Figure 1. Illustration of issues associated with atmospheric transport. Pollution may be generated in Area A, with considerable removal by vegetation in Area B, which has the greatest benefit for the population in Area C.

One solution to the problems outlined above is to use atmospheric chemistry transport models (ACTMs), which incorporate atmospheric physical transport and chemical processes, interactions between pollutants, driven by (real) meteorological parameters, thus avoiding many of the pitfalls of more static calculation techniques. In addition, state-of-the-art ACTMs comprise detailed surface-atmosphere exchange processes, explicitly modelling the dry and wet deposition processes in general, and the interaction between atmospheric pollutants and vegetation specifically. This approach has the added advantage that it allows calculation of health benefits directly from a change in exposure (i.e. a change in pollutant concentration), rather than indirectly via damage costs per unit of pollutant emitted.

An additional challenge relates to how to define 'urban' in the context of a national account. Most definitions of urban are based on either land cover, or administrative boundaries. Both approaches cause problems when trying to develop an urban account. For land-cover based definitions based on optical or radar data, most classifications of 'urban' or 'sub-urban' include a combination of small gardens, roads and buildings since satellite imagery cannot resolve the fine-grained variability in these features satisfactorily, but they exclude larger green and blue spaces in urban areas. These are classified as other land covers (i.e. grassland or woodland in public parks, rivers, etc.). However, these are a significant part of the urban fabric and should therefore be considered 'urban' in the context of urban natural capital accounts. An assessment based purely on land-cover would exclude these larger components of urban areas. The opposite problem arises with using boundaries corresponding to administrative authorities. These usually include substantial areas of rural habitat surrounding the urban area. In the UK for example, this can contain agricultural land, moorland or woodland. A natural capital assessment based purely on administrative boundaries will therefore over-estimate the amount of green or blue space in an urban area. National agencies sometimes hold urban boundary layers based on morphology, but these still tend to exclude larger areas of greenspace, and particularly large rivers which flow through urban areas. An urban natural capital assessment needs to include these green and blue space elements that are typically considered part of the urban fabric, but should exclude the surrounding rural area.

Therefore, in this paper we develop a sophisticated approach to calculate a natural capital account for pollution removal by urban vegetation, using Great Britain as an example and applying it to encompass all urban areas across the country. We use an atmospheric dispersion model to calculate changes in pollutant concentrations as a result of pollution removal by vegetation. From the resulting change in exposure we estimate the health benefits in terms of reduced respiratory and cardiovascular hospital admissions, reductions in Life Years Lost, and reductions in early mortality. We estimate the economic value as Net Present Value and the 100-year asset value for urban natural capital across Great Britain, and demonstrate reporting of the asset account, the physical flow account, as well as health and monetary accounts. In constructing this approach we also propose a new way to define the urban boundary that satisfies the requirements of a national-level urban account.

2. Methods

2.1. Urban extent

In order to create an urban natural capital account, the first requirement for the physical account was to develop a definition of ‘urban’ and corresponding spatial boundaries that satisfied the following requirements:

- Intuitive – encompassing all aspects of what city dwellers would consider part of their urban environment, e.g. rivers, parks, woodland.
- Reflective of changing land use – i.e. must be able to capture urban change and urban expansion over time.
- National level – must be applicable for any urban area in the country and across the whole country

The approach used an existing urban morphology GIS layer from the Office of National Statistics, modified so that it incorporated areas of green and blue space within cities. Rather than manually digitising boundaries, a set rule was developed to calculate the boundary to allow efficient automation of the procedure for all urban areas in Britain, and to allow repeat use in a consistent way for future iterations of the account. The methodology involved applying a variable sized buffer to each polygon in the existing morphology layer (ONS BUA2011 data layer) for England and Wales (Jones et al. 2017). The size of the added buffer was proportional to the size of the polygon. We then dissolved overlapping boundaries for each polygon and then reduced the new boundary by the same buffer width. The effect of this procedure is to draw in any areas enclosed by the buffer (i.e. if the outer edges of buffered zones meet then it captures the entire area). This draws in patches of land that are mostly surrounded by urban built-up-areas, such as the River Thames and large parks in central London. This is illustrated in Figure 2. Initially, two buffer widths of fixed size were trialled, one capped at a maximum of 250 m, the other at 500 m, which revealed that a variable buffer was needed. The final approach used a variable buffer which was a function of the size of the polygon, using equation 1.

$$\text{Buffer width} = 0.012*\sqrt{\text{Polygon area}} \tag{1}$$

The calculation was scaled to give a buffer of approximately 500 m for a polygon the size of Greater London (1738 km^2). This proportional approach was applied so that small built-up-areas do not have a large buffer applied to them. The buffer applied to the smallest urban area (Eardington – a small (20 ha) village and civil parish in Shropshire, England) was 5 m, compared with 500 m for Greater London. The same approach was applied to the equivalent Scottish and Northern Ireland built up area layers to create an urban boundary layer for Britain.

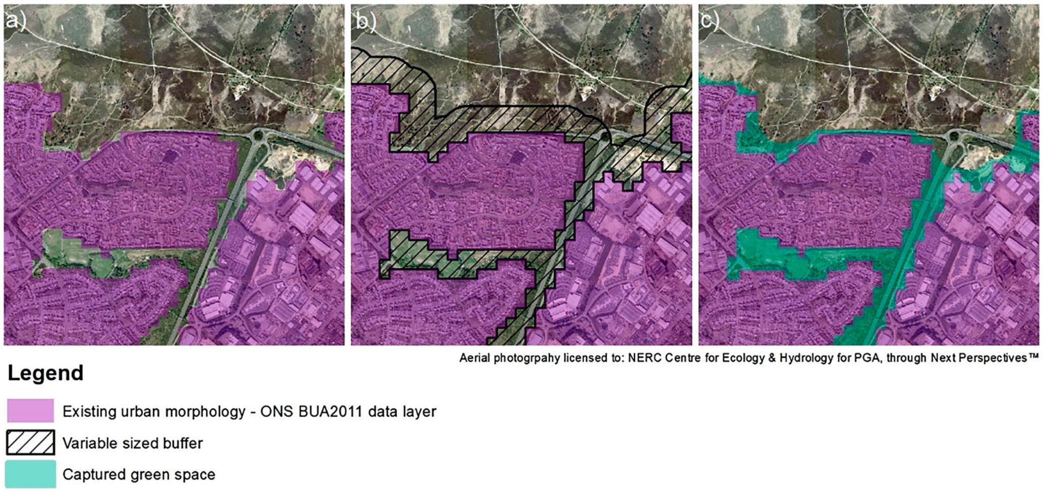

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Figure 2. Illustration of how the variable buffer captures areas of urban green space not initially included in the built up area morphological definition of 'urban', showing (a) initial morphology layer, (b) layer with additional variable buffer, (c) buffer collapsed back, showing area captured.

2.2. Natural capital

The stock of natural capital providing the service is the natural or semi-natural surfaces, including vegetation and water bodies, with stock defined in terms of its extent. Within all urban boundaries defined above, urban natural capital was defined as three green and blue space components. These were:

- Urban woodland
- Urban grassland
- Urban fresh/saltwater

We created a hybrid landcover layer with a national data product at 25 m resolution (CEH Landcover map 2007, Morton et al. 2011) outside of urban areas, and a finer resolution layer using a national mapping product for areas within the urban extent. The mapped data were derived from the OSMasterMap 'natural surface' category, for the three urban classes above. Woodlands were identified as any objects with the term 'trees' or 'woodland' in the main descriptor field, since woodland was not mapped as a separate category in this dataset, the remainder was classified as urban grassland, to encompass all other non-woody urban vegetation. In the 'outside urban' areas, the 27 land classes were aggregated to seven classes for input to the EMEP4UK atmospheric transport model described below. The seven classes were: deciduous woodland, coniferous woodland, crops, semi-natural i.e. grassland & heathland, water, urban and bare soil.

2.3. Selection of pollutants for modelling health impacts

Selection of pollutants considered a number of factors, which included: the ability to model them dynamically, their importance from a health-impact perspective, and the availability of dose-response relationships to calculate health impacts. The EMEP4UK model provides outputs for thirteen pollutants, of which six are routinely implicated in health impacts (SO_2, PM_{10}, $PM_{2.5}$, NO_2, NH_3 and O_3). Of these, only four pollutants were chosen for this analysis (SO_2, $PM_{2.5}$, NO_2 and O_3) due to their contribution to health impacts and the availability of dose-response functions from international working groups such as COMEAP. $PM_{2.5}$ includes particles that are directly emitted (primary particles) and secondary particles formed in the atmosphere including aerosols of nitrate, sulphate and ammonium as well as black carbon and other organic compounds and trace metals (Rehm, Taylor, and Room 2006). The role of SO_2 in generating health impacts in western Europe has greatly declined over the last 40 years due to the success of emission control policies in urban areas, but SO_2 was still included for comparison with other published studies. Pollutants not included were PM_{10} and NH_3. For PM, the majority of health impacts attributed to particulate matter are caused by the $PM_{2.5}$ fraction, which are a subset of the PM_{10} definition. $PM_{2.5}$ comprises the fine fraction of particulate matter considered most damaging to human health, as its size means that it can penetrate deep into the lung. For NH_3, the primary health effects occur via ammonium aerosols which are a component of the $PM_{2.5}$ fine particulate fraction. Therefore, the health effects of NH_3 are considered within the $PM_{2.5}$ assessment, rather than separately.

2.4. Description of EMEP4UK model and data inputs

EMEP4UK (Vieno et al. 2016) is a dynamic atmospheric chemistry transport model. The model takes emission sources, meteorology and a land-cover layer as inputs and calculates atmospheric concentrations directly from the inputs, incorporating chemical and meteorological interactions, including with vegetation and soils, dynamically on an hourly timestep. The EMEP4UK version rv4.17 used in this study is based on the official EMEP MSc-W model (Simpson et al. 2012). The EMEP4UK model use a latitude-longitude grid and 21 vertical layers with thickness varying from ~40 m at the surface to ~2 km at the top of the vertical boundary (~16 km). The EMEP4UK model domain covers all Europe, part of North Africa, part of Russia and part of East Asia at a horizontal resolution of $0.5° \times 0.5°$. A nested domain covering the British Isle uses a resolution of $0.055° \times 0.055°$ (approximately 5×5 km). The major difference between the official EMEP MSc-W model and the EMEP4UK is the meteorological driver. EMEP4UK uses WRF version 3.7.1 as its meteorological input, using hourly 3D meteorological data. The WRF model is initialised and nudges every 6 h using the Global Forecast system final reanalysis (GFS-FNL) data (National Centers for Environmental Prediction, 2015).

The emissions used in the EMEP4UK rv4.17 model are derived from the NAEI emissions estimate for the UK, the EMEP emissions estimate for the remaining EU, the Finnish Meteorological institute (FMI) estimate for shipping emissions (Jalkanen, Johansson, and Kukkonen 2016), and the default EMEP emissions (based on the year 2005) for the remaining part of the EMEP4UK domain (i.e. the part of north Africa included in the current domain). Forest fire emissions were not included in this work.

2.5. Description of scenarios

The dynamic nature of the EMEP4UK model means that a scenario approach was required to establish the role of urban natural capital in pollutant removal. Calculations were run for two years, 2015 and future projections to 2030. For each year, two scenarios were run, the first with current UK land cover, using the hybrid landcover layer described above, the second with all urban natural capital land classes removed and replaced with a neutral surface equivalent to bare soil, but with dust suspension from soil turned off in the model. In order to calculate the effects of natural capital, outputs from the second scenario were extracted from the first. This approach allows all of the interactions with meteorology and other pollutants to continue as normal, while controlling for the presence and type of vegetation.

2.6. Description of health functions and economic benefits

The economic and health calculations for the monetary account can take two approaches. (i) Application of damage costs to the quantity of pollutant removed (Tier 1 approach); (ii) Applying a health analysis to estimates of change in pollution concentrations in order to calculate economic benefit based on the exposure of the population (Tier 2 approach). In this study, we applied the more complex Tier 2 approach, based on damage cost per unit exposure, calculating the economic benefit directly from mortality and morbidity data for each local authority in the UK, and the change in pollutant exposure of the receiving population. The monetary account is therefore split into three components:

- The health benefit arising from the service of air pollution removal
- The monetary account of that health benefit
- The future asset value of that health benefit

The quantification of short term impacts on mortality and on hospital admissions is a straightforward multiplication of population weighted concentrations, population, rate of illness and response function. Quantification of long term impacts on mortality instead uses a life table approach (COMEAP 2010). Life tables describe the structure of the population, accounting for inputs (births and immigration) and outputs (deaths and emigration). Changes in the risk of mortality (calculated by combining pollution data and response functions) affect the number of people moving from one age class to the next in successive years. Deaths from non-natural causes are excluded from the analysis (3.1% of all UK deaths[1]). Health functions and values used are summarised in Table 1.

'Life years lost' is calculated from the life tables as the aggregate loss of life expectancy attributable to pollution exposure. Unlike QALYs (Quality Adjusted Life Years), it is not weighted for health status in any way (unlike 'quality adjusted life years'). Valuation data are taken from Defra recommendations. Mortality and hospital admissions are valued from the perspective of willingness to pay, drawing on an earlier study by Chilton et al. (2004) for Defra. For ozone, deaths are valued at £6000 (2012 price), calculated by assuming that each ozone related death leads to the loss of (on average) 4 months of life, using a VOLY (Value Of Life Years) of £18,000 assuming that those affected are already in poor health. Life years lost associated with exposure to $PM_{2.5}$ and NO_2 are valued at £35,000 (2012 price), assuming those affected are in 'normal health'.

Economic valuation or morbidity and mortality data are taken from Defra recommendations (IGCB 2011):

Mortality: values are estimated for life years lost (i.e. death being brought forward) associated with air pollution. The primary source of this valuation evidence is the paper by Chilton et al. (2004),

Table 1. Mortality and morbidity functions used in the evaluation of health benefits.

		Change in risk per 10 μg/m^3	Age group	Rate per person	Value, £ (2012)	Source
$PM_{2.5}$	Respiratory hospital admissions	1.09%	All age	0.01139	6650	Atkinson et al. 2014
	Cardiovascular hospital admissions	0.91%	All age	0.01300	6450	Atkinson et al. 2014
	Life years lost (as a result of long-term exposure)	6.00%	All [a]	1.00000	35,000	COMEAP 2010
SO_2	Respiratory hospital admissions	0.50%	All age	0.01139	6650	Defra 2013
NO_2	Respiratory hospital admissions	0.52%	All age	0.01139	6650	Mills et al. 2015
	Cardiovascular hospital admissions	0.42%	All age	0.01300	6450	Mills et al. 2015
	Life years lost (as a result of long-term exposure)	0.92%	All [a]	1.00000	35,000	COMEAP 2017
O_3	Respiratory hospital admissions	0.75%	All age	0.01139	6650	COMEAP 2015 ozone
	Cardiovascular hospital admissions	0.11%	All age	0.01199	6450	COMEAP 2015 ozone
	Deaths (as a result of short term exposure)	0.34%	All age [b]	0.00915	6000	COMEAP 2015 ozone

[a] % change fed into life tables to generate adjustment factor.

[b] Calculated as £18,000 per life year * 4 months/ death.

which uses a stated preference (contingent valuation) methodology to estimate the value of a life year (VOLY) based on willingness-to-pay to avoid lost life years. These values range from £18,000 (assuming life expectancy losses are in poor health) to £35,000 (assuming life expectancy losses are in normal health) (Defra 2014). For the purposes of this work the values were applied as follows:

Ozone related deaths are valued at £6000 (2012 price). This has been calculated by assuming that each ozone related death leads to the loss of (on average) 4 months of life, using a VOLY (Value Of Life Years) of £18,000 assuming that those affected are already in poor health. PM2.5 and NO2 related deaths are valued at £35,000 (2012 price), assuming those affected are in 'normal health'.

As noted in the Defra (2013) guidance, there are a number of uncertainties surrounding the values that need to be taken into account when interpreting the results of the analysis. In particular, there are uncertainties surrounding: the amount of life expectancy lost due to the acute effects of air pollution; the quality of the life expectancy lost due to the acute effects of air pollution; the quality of the life expectancy lost due to the chronic effects of air pollution; the ability of respondents within the contingent valuation study to accurately value losses of life expectancy in poor health or to grasp the concept of loss of life years in normal health (as opposed to losses at the end of life); and the accuracy with which study respondents valued morbidity effects.

It is noted that outside of the UK the use of the value of statistical life (VSL) is far more widespread. Using this approach the estimated values would be significantly higher, (by roughly a factor 4 if using the recommendations from OECD 2012).

Reductions in the actual resource cost savings from reduced hospital admissions could provide an alternative valuation (as is used in morbidity for valuation). Estimates of the total (including morbidity) NHS and social care costs of $PM_{2.5}$ and NO_2 pollution are only ~£45 m/yr (Gowers, Miller, and Stedman 2014). This suggests that estimates of the avoided resource costs associated specifically with reduced mortality impacts due to natural capital would result in much lower aggregate values than the willingness-to-pay values used. However, these resource costs are not as relevant as WTP estimates for valuing mortality because for example, some diseases are not very costly since there is not much that can be done to alleviate them and the patient dies quickly.

Morbidity: the value of reduced incidences of certain illnesses ranges from £2600 to £10,700 (central estimate £6650) for respiratory hospital admissions and £3000 to £9900 (central estimate £6450) for cardiovascular hospital admissions (Defra 2014) based on reductions in three key forms of health care costs: *Resource costs*: the medical costs to the National Health Services and private costs of dealing with the illness, these are exchange values; *Opportunity costs*: the lost productivity and opportunity cost of leisure (including unpaid work) which are valued based on salary costs of absent individual (i.e. exchange value); and *Disutility*: disutility of ill health to the individual and their family and friends which is a willingness-to-pay value.

2.7. Data on incidence and prevalence of disease

Data on mortality rates were taken from national statistics, providing data on the number of deaths for 2015 from national statistics, and a projection for 2030 (the principal projection was used). Data on UK incidence of hospital admissions was taken from WHO's European Hospital Morbidity Database.[2] Data on the variation in hospital admissions around the country, by Local Authority, were taken from work carried out by the British Lung Foundation (BLF 2017). The BLF study focused on respiratory hospital admissions, but it was assumed here that the same pattern of disease applies also to cardiovascular admissions. Population data were taken from official statistics for England, Wales and Scotland.

For each pollutant, a population-weighted average change in concentration was calculated at local authority level, using a spatially attributed population map from the CEH Environmental Information Data Centre (Reis et al. 2016) and EMEP4UK pollutant data, both assessed at 1 km resolution. The exposed population was calculated using a population-weighted change in concentration, and current or projected population for each year, by local authority.

2.8. Description of economic functions

This account values the natural capital assets based on the present value of the stream of (annual) environmental benefits that the assets will provide over a future period of time. Estimation of long-term asset values is calculated over a 100 year period with income uplift. In calculating the long-term asset value we incorporated changes in the following variables each year: For physical service flows, the profile of forecast changes in pollutant concentrations was an input to the model for the 2030 run. Land cover and meteorology were kept constant for both years. For monetary value, growth of the beneficiary population over time was based on population projections by area of Britain. Dose-response functions for health were assumed to remain constant over time. Future flows of ecosystem services are projected to 35 years after which they are assumed to remain constant and monetary values are discounted at a declining rate starting at 3.5%, in line with the Defra and ONS (2017) principles paper to be followed when developing natural capital accounts in the UK as part of the ONS Environmental Accounts. For uplift, health values were uplifted by 2% per year following Defra (2014) air pollution valuation guidance, since willingness to pay (WTP) is likely to increase over time in line with increases in wealth (Defra 2014). Thus, values were adjusted based on the GDP deflators (HM Treasury 2017) and then the 2% uplift was applied. The economic value is attributed to the UKNEA broad habitats at a national level, by apportioning the total economic value of pollutant removal to the total amount of pollution removed by each urban natural capital type.

3. Results

3.1. Asset account

The asset account is the natural capital which provides the service of pollution removal. The extent of the urban natural capital calculated in this assessment is shown in Table 2. Together the natural capital green and blue space components occupy 30% of the total urban area, with the remaining 70% consisting of urban infrastructure such as buildings and roads or mixed surfaces which includes pavements and road verges etc. which are too small to be mapped as discrete units. Of the urban natural capital, grassland makes up the largest fraction at 23%, woodland at 5.5%, while water occupies only 1%.

3.2. Physical flow account

The physical flow account represents the quantity of pollutants removed from the atmosphere by the urban natural capital (Table 3). In 2015, urban green and blue space across Britain removed 26.6 kt of $PM_{2.5}$, SO_2, NO_2 and O_3 (28.7 kt when combined PM_{10} and $PM_{2.5}$, and NH_3 are also included). By weight, over 75% of the pollution removed is ozone, however although much smaller by weight, the more important pollutant in terms of health impacts is $PM_{2.5}$. Negative values for some pollutants removed by urban water are valid outputs resulting from the scenario comparison, and suggest that dry deposition to water would actually be greater if there were no woodland or grassland present.

Table 2. Physical extent account of urban natural capital. Area of the habitats providing the service (ha), extracted from OS Mastermap.

Habitat	Area (ha)	% of urban extent
Urban woodland	97,600	5.5
Urban grassland	412,400	23.4
Urban freshwater/saltwater	19,474	1.1
Buildings, sealed surfaces and mixed surfaces	1,236,226	70.0
Total urban extent (GB)	1,765,700	

Table 3. Pollutant capture by urban natural capital, as dry deposition of pollutants (ktonnes per year), and showing removal rate (kg per ha of habitat). Negative values are valid model outputs. * excludes $PM_{2.5}$ as a subset of PM_{10}.

Pollutant	Habitat	Kt/yr removed in Britain 2015
PM_{10}	Urban woodland	1.23
	Urban grassland	0.45
	Urban water	−0.004
	Total urban natural capital	1.68
$PM_{2.5}$	Urban woodland	0.70
	Urban grassland	0.31
	Urban water	−0.003
	Total urban natural capital	1.01
SO_2	Urban woodland	0.59
	Urban grassland	1.00
	Urban water	0.049
	Total urban natural capital	1.65
NH_3	Urban woodland	0.44
	Urban grassland	0.95
	Urban water	0.045
	Total urban natural capital	1.43
NO_2	Urban woodland	0.41
	Urban grassland	1.61
	Urban water	0.000
	Total urban natural capital	2.02
O_3	Urban woodland	4.97
	Urban grassland	16.94
	Urban water	−0.003
	Total urban natural capital	21.91
All pollutants*	Urban woodland	7.65
	Urban grassland	20.95
	Urban water	0.087
	Total urban natural capital	28.68

The next component of the physical flow account is the intermediate step of 'clean air'. In this case, the reduction of gaseous pollutant concentrations across the country. This represents the change in exposure of the population which delivers the actual health benefits.

Table 4 shows the average concentrations of each pollutant, and the change in concentration from the scenario runs. Note this is the average concentration across the whole of Great Britain, not just in urban areas. Urban vegetation also affects pollutant concentrations outside of the urban areas, so the full analysis needs to account for all of these health benefits. Figure 3 shows the spatial pattern of change in concentration (and therefore exposure of the population) of $PM_{2.5}$. The greatest change in $PM_{2.5}$ reflects the location of large urban areas across the country. The average reduction in concentration of $PM_{2.5}$ across Britain due to pollution removal by urban natural capital is around 0.38%, ranging from a 0.10–0.84% reduction (0.05 & 0.95 percentiles). The absolute change in $PM_{2.5}$ across Britain is $-0.03\ \mu g\ m^{-3}$. However, it should be noted that in this UK study, this represents an average across the whole land area, not just the urban extent. The reduction in concentrations is more marked in urban areas with an average percentage change in urban grid cells of 0.79% reduction (ranges from 1.67% to 0.27% reduction). The absolute change in $PM_{2.5}$ concentrations for urban grid cells is $-0.07\ \mu g\ m^{-3}$, ranging from -0.16 to $-0.02\ \mu g\ m^{-3}$.

3.3. Monetary flow accounts – the health account

Across all pollutants in 2015, there were 900 fewer respiratory hospital admissions, 220 fewer cardiovascular hospital admissions, 240 fewer deaths and 3600 fewer Life Years Lost as a result of pollution removal by urban green and blue space (Table 5). Approximately three quarters of the avoided health impacts are due to reductions in $PM_{2.5}$ concentrations. Most of the remaining health value is

Table 4. Average concentrations across Great Britain from the EMEP4UK model in the two scenarios, and absolute change in concentration and relative difference (%) which represents the effect of urban green/blue space. Negative values show a reduction in pollutant concentration due to removal by urban green/blue space (μg m^{-3}).

Pollutant	Habitat	2015
PM_{10}	Current vegetation	13.62
	No vegetation	13.66
	Absolute difference	−0.04
	Difference (%)	−0.29
$PM_{2.5}$	Current vegetation	6.21
	No vegetation	6.24
	Absolute difference	−0.03
	Difference (%)	−0.44
SO_2	Current vegetation	0.77
	No vegetation	0.78
	Absolute difference	−0.01
	Difference (%)	−1.83
NH_3	Current vegetation	1.41
	No vegetation	1.42
	Absolute difference	−0.01
	Difference (%)	−0.90
NO_2	Current vegetation	4.66
	No vegetation	4.69
	Absolute difference	−0.03
	Difference (%)	−0.61
O_3	Current vegetation	66.6
	No vegetation	66.7
	Absolute difference	−0.2
	Difference (%)	−0.25

due to NO_2 removal. The greatest change in respiratory hospital admissions comes from Ozone concentrations.

3.4. Monetary flow accounts – Net Present Value and asset value

The total value of avoided health impacts due to urban green and blue space is just over £136 m in 2015 (Tables 6 and 7). When partitioned by habitat, roughly three quarters of this health benefit is due to removal of $PM_{2.5}$, in large part by urban woodland (Table 6). Much of the remainder is due to removal of NO_2 which, by contrast, is removed by grassland. Removal of SO_2 accounts for less than 1% of the value, reflecting the very low concentrations of this pollutant in Britain currently. When partitioned by health impact, the greatest value comes from avoided Loss of Life Years (Table 7). The

Table 5. Change in mortality and morbidity of UK population as a result of air pollution removal by urban green/blue space.

Pollutant	Health impact	2015 no. yr^{-1}
$PM_{2.5}$	Respiratory hospital admissions	−58
	Cardiovascular hospital admissions	−51
	Life years lost	−2733
SO_2	Respiratory hospital admissions	−30
NO_2	Respiratory hospital admissions	−63
	Cardiovascular hospital admissions	−53
	Life years lost	−908
O_3	Respiratory hospital admissions	−749
	Cardiovascular hospital admissions	−116
	Deaths	−239
All pollutants combined	Respiratory hospital admissions	−899
	Cardiovascular hospital admissions	−220
	Life years lost	−3641
	Deaths	−239

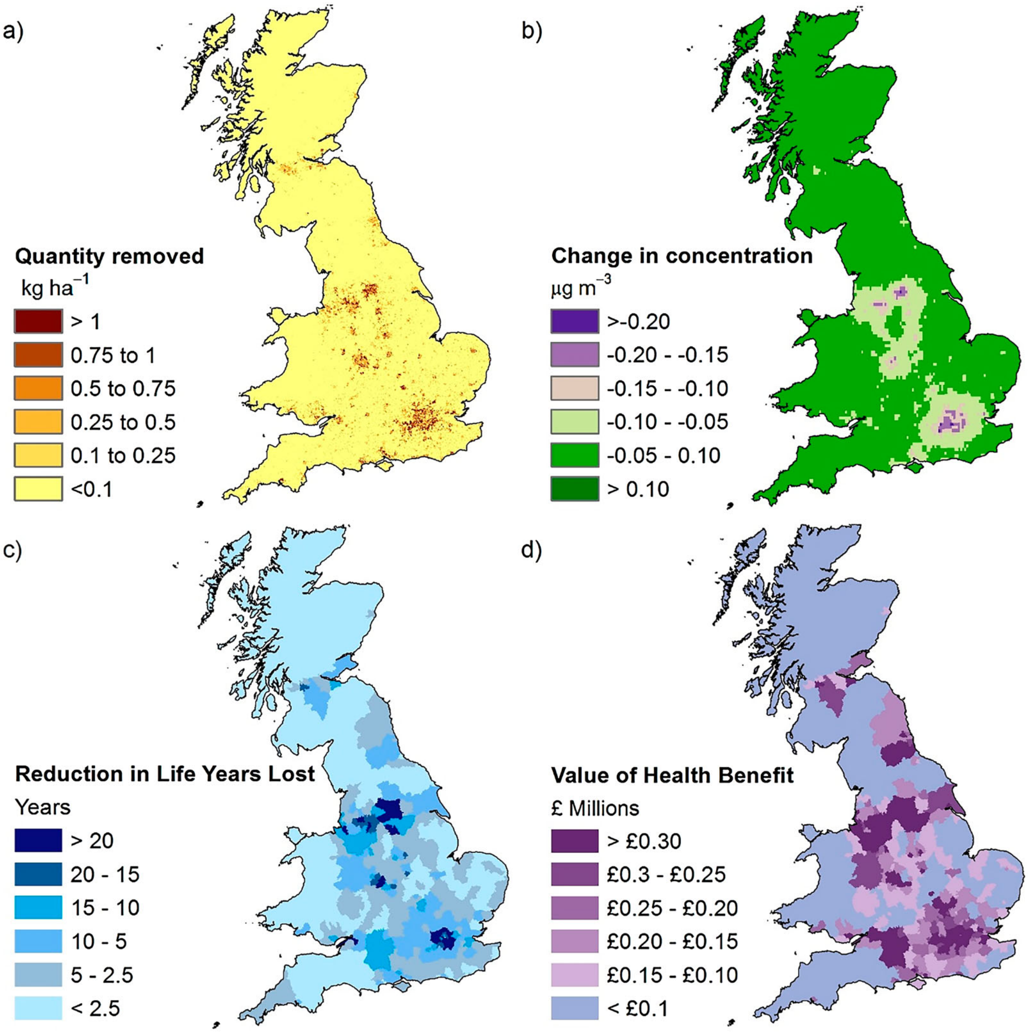

Figure 3. Maps show the varying spatial pattern of $PM_{2.5}$ removal and its benefits across Britain, showing: (a) quantity of $PM_{2.5}$ removed by urban natural capital (kg ha^{-1} of urban area), (b) change in concentration of $PM_{2.5}$ (µg m^{-3}), (c) reduction in number of Life Years Lost, by Local Authority, (d) value of health benefit from reduced pollutant exposure, in Net Present Value (£m), by Local Authority.

long term asset value of urban natural capital, calculated over a 100 year period with income uplift, is £5.1 bn for 2015.

4. Discussion

In this study, we have derived a consistent way to create a boundary for urban extent that is suitable for calculating a national-level urban natural capital account. We have applied a dynamic modelling approach to calculate pollution removal by urban vegetation which takes into account chemical interactions among pollutants and meteorology, and which takes into account the transport of both pollutants, but also the benefits in terms of reduced pollution concentrations, across urban areas.

A large part of the health benefits are due to woodland because of the high rates of PM removal by trees. This is primarily a result of their high surface area, but is also influenced by the co-location of

Table 6. Monetary value of the health benefits pollution removal in 2015, by habitat, (Net Present Value, rounded to nearest £1000).

Pollutant	Habitat	2015
$PM_{2.5}$ all health effects	Urban woodland	£67,011,000
	Urban grassland	£29,651,000
	Urban water	−£286,000
	Total urban natural capital	£96,376,000
SO_2 all health effects	Urban woodland	£71,000
	Urban grassland	£120,000
	Urban water	£6000
	Total urban natural capital	£197,000
NO_2 all health effects	Urban woodland	£6,586,000
	Urban grassland	£25,964,000
	Urban water	−£5000
	Total urban natural capital	£32,545,000
O_3 all health effects	Urban woodland	£1,626,000
	Urban grassland	£5,536,000
	Urban water	−£1000
	Total urban natural capital	£7,160,000
Total pollutants	Urban woodland	£75,294,000
	Urban grassland	£61,271,000
	Urban water	−£286,000
	Total urban natural capital	£136,279,000

Table 7. Annual value and asset value (with income uplift) of air quality regulation from urban green/blue space, for the urban account, as measured by the present value of the stream of annual ecosystem services that the assets provide. Note difference in units.

		2015	
Pollutant	Health impact	Annual value £ million /yr	Long term Asset value £ million
$PM_{2.5}$	Respiratory hospital admissions	0.4	16.3
	Cardiovascular hospital admissions	0.3	13.9
	Life years lost	95.7	3808.5
SO_2	Respiratory hospital admissions	0.2	7.6
NO_2	Respiratory hospital admissions	0.4	10.4
	Cardiovascular hospital admissions	0.3	8.5
	Life years lost	31.8	747.0
O_3	Respiratory hospital admissions	5.0	366.6
	Cardiovascular hospital admissions	0.8	54.9
	Deaths	1.4	99.8
	Total	136.3	5133.3

trees and high PM concentrations in the assessment. Comparing these results with those of the i-tree London assessment (Rogers et al. 2015), the i-tree study calculated 2057 tonnes of pollutants removed by trees in London (encompassing NO_2, combined PM_{10} & $PM_{2.5}$, SO_2 and O_3). For the same pollutants, counting removal by trees only, and scaling our results to estimate the equivalent for the area of London, assuming that the proportion of green and blue space is similar in London to the British average, this study calculates 651 tonnes of pollutants removed. So, compared with i-tree we estimate a smaller quantity of pollution removal. For most pollutants, our estimates are roughly half of those estimated by i-tree, probably reflecting a coarser measure of the area of tree cover than was used as input to i-tree. There is a larger difference for NO_2 removal, the reasons for which are discussed below.

For economic value, the i-tree study calculated a value of pollution removal for four of the pollutants above (excluding PM_{10}) of £62.7 m. For the same pollutants in our study, and scaling the Britain value down to London by population, we estimate a value of £10.0 m. Although quantities of pollutant removed are roughly half those in the i-tree study, a further reason for the much lower estimate of value in our study is that the quantities of NO_2 removed by vegetation are considerably lower than i-tree. This reflects a realistic assumption in the EMEP4UK model that although trees remove NO_2 from the atmosphere, at the same time there are natural NO emissions from the soil under trees, and these values cancel each other out to a large extent. The latest thinking on quantifying health impacts from NO_2 is also changing. A recent report (COMEAP 2018) takes a considerably more cautious approach to quantification of NO_2 related mortality than previously adopted. Whilst the report finds good evidence for an additional effect beyond that quantified for particles alone, it suggests that the estimates of mortality associated with PM and NO_2 should not be considered additive. If that is the case, the NO_2 contribution to damage reported here should be eliminated. This would make roughly 10% difference to the totals reported here, but has implications for interpreting results of previous studies.

The average reduction in concentration of $PM_{2.5}$ in urban areas of Britain due to pollution removal by urban natural capital of around 0.79% corresponds closely to that reported in Nowak et al. (2014), and are relatively small. However, the health benefits of this reduction in concentration are considerable, and are influenced by the fact that most beneficiaries live in urban areas.

While this study estimates health benefits of reducing air pollution, we note that air pollution will be one of a number of factors affecting the cardiovascular and respiratory systems, along with diet, exercise levels, smoking behaviour, etc. COMEAP (2010) concludes that the number of deaths that may be associated with air pollution to some degree is likely to be higher than the number quantified by this and other analyses, e.g. 30–40 k people per year in the UK (RCPCH 2016), though the lower figure can be interpreted as 'equivalent attributable deaths', an amalgamation of impact over all those affected to some degree. It is noted that outside of the UK the use of the value of statistical life (VSL) is far more widespread. Using this approach the estimated values would be significantly higher, (by roughly a factor 4 if using the recommendations from OECD 2012).

Strengths of this study are that it uses a dynamic approach to calculate changes in pollutant concentrations, and is therefore able to calculate how vegetation in one area can result in health benefits downwind. This is important because a sizeable proportion of pollution in urban areas is actually derived upwind e.g. secondary aerosol $PM_{2.5}$ from rural ammonia. Not all of it is generated *in-situ* from urban emission sources. It also uses a more sophisticated calculation of the health benefits than other studies which use damage costs based on tonnes of pollutant removed. One limitation is the fairly coarse resolution (from an urban perspective) of the chemical interactions. Even though fine-scale information (<25 m) on the extent of urban natural capital is fed into the model, this is not spatially defined within a grid cell. At present, the model results give a picture of the overall quantity of pollution removed and the change in concentration at a grid cell level. Improving the spatial resolution of the chemical interactions would allow finer scale planning of the best locations for urban natural capital to achieve maximum benefit in reducing exposure of the population to harmful levels of air pollution. Lastly, we note that the best way to reduce air pollution impacts is to reduce pollution at source. A UK modelling study conducted in the West Midlands suggested that even if all available space in a city were to be planted with trees, the maximum likely reduction in pollution (PM_{10}) concentrations was in the order of 25% (McDonald et al. 2007). Therefore, as this urban account shows, natural capital can help as part of the solution and has economic benefits, but it will not fully solve the problem.

Notes

1. http://www.endoflifecare-intelligence.org.uk/view?rid=117.
2. http://data.euro.who.int/hmdb/.

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