Annex 1: Background and methods for experimental pollution removal estimates

The methods, estimates and analysis in this annex were developed by AECOM for the ONS. It contains the following subsections:

- Background to the project
- Methodology
- Results, including answers the following questions:
  - question 1: How much PM_{10} and SO_2 was absorbed by the UK's natural capital in 2012 and what was the value of this service?
  - question 2: How do the results compare to the i-Tree assessment "Valuing London's Urban Forest"?
  - question 3: How did the quantity and value of this service change over the period between 2006 and 2012?
  - question 4: How do the estimates of PM_{10} and SO_2 absorption differ across the Corine and Land Cover Map datasets?
- Conclusions
- Limitations and further recommendations

Background to the project

Traditionally, economic progress is measured through the System of National Accounts (SNA) which provides an international standard for measuring national income and savings in order to gauge and compare countries' economic activity.[1] Most countries rely on gross domestic product (GDP) as a measure of economic performance. However, GDP is a measure of income that is not adjusted for the capital costs associated with using the assets that underpin the generation of the income. Moreover, national accounts do not routinely incorporate the benefits derived from the services that nature provides "for free", such as clean water, clean air, and protection against flooding.

The Department for Environment, Food and Rural Affairs' (Defra) 2011 Natural Environment White Paper (NEWP) committed the government to *"put natural capital at the centre of economic thinking and at the heart of the way we measure economic progress nationally"*.[2] Moreover, it committed Defra to work with us at the Office for National Statistics (ONS) to fully include natural capital in the UK Environmental Accounts. In late 2012, we published a "roadmap" for doing so which included proposals for the development of three different types of accounts:

- top-down accounts that provide an overview of the value of the UK's ecosystem services within the framework of comprehensive wealth accounts
- enabling/cross-cutting accounts that cover land use/land cover and carbon and provide the basic framework for the development of accounts relating to specific habitats
- bottom-up or habitat-based accounts for particular ecosystems which aim to encompass the extent and condition

[1] See: UN Stats' System of National Accounts .

[2] HM government (2011). The Natural Choice: securing the value of nature.

of the relevant ecosystem assets and also provide for measures of the flows of different ecosystem services.

Good progress is being made with the latest 2014 UK environmental accounts, including experimental accounts for land use and forestry. In addition, in July 2014 Defra and the ONS published Principles of Ecosystems Accounting to set out guidelines for undertaking ecosystem accounting in the UK. In 2015, a series of further studies were published, including Natural Capital Accounting 2020 Roadmap: Interim Review and Forward Look, freshwater assets and services accounts, as well as scoping studies for peatlands, woodlands, and marine ecosystems.[3]

The work undertaken in the UK draws from and builds upon the UN System of Environmental-Economic Accounting (SEEA) Central Framework[4] and the complementary framework for undertaking ecosystem accounting – SEEA Experimental Ecosystem Accounting (SEEA EEA).[5,6] These initiatives provide a framework where information on multiple ecosystems generating multiple services can be brought together at a national level to inform policy, support long-term monitoring of ecosystem condition and provision of services, and to evaluate the success of national strategies targeting improvements in ecosystem services.

At its core, the SEEA EEA approach reflects the relationship between stocks of assets and the flows of services that they generate. The measurement of assets in ecosystem accounting starts with the measurement of ecosystem condition and the extent to which it is intended to provide measures of the stock of ecosystems and the change in their capacity to provide services over time.

The development of the SEEA Central Framework emerged from long standing discussion among statistical offices on the integration of environmental information into the standard economic or national accounts. Until the SEEA EEA, efforts had focused largely on the measurement of natural resources and physical flows of water and energy into and within the economy. While the effects of economic activity on ecosystems have long been recognised, difficulties in quantifying and measuring ecosystem assets and flows have inhibited the development of ecosystem accounts.

In late 2014, Defra commissioned AECOM to draw on the SEEA EEA to develop pilot ecosystem accounts for a selected suite of protected areas (national parks and areas of outstanding natural beauty) in England, and land use strategy (LUS) pilot areas in Scotland, that consist of a variety of ecosystems providing multiple services. In addition to quantifying the extent and condition of ecosystem assets within the pilot area boundaries, the project also quantified and valued (where possible) the physical and monetary flows of ecosystem services from these assets.

The value of the air quality regulation service was estimated based on the amount of PM_{10} absorbed by different habitats. Defra air quality damage cost guidance[7] was then used to calculate the avoided damage cost for absorption of PM_{10}. The results suggested that air quality regulation is one of the most economically valuable ecosystem services provided by the UK's natural capital, with the total annual flows of this service in 2013 reaching £323 million in Aberdeenshire alone. The highest rate of PM_{10} absorption was found to be within woodland ecosystems, in particular coniferous woodland. It was also found that there could be significant additional benefits from woodland located in polluted areas within and around extended urban areas.

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[3] Defra and ONS (2015), Natural capital publications

[4] The "Central Framework", adopted in 2012, covers physical flows (for example, for energy, water and materials), environmental activities (for example, environmental protection expenditure on the part of government) and asset accounts (for example, for minerals, energy, soil, timber as well as land and aquatic resources).

[5] United Nations (UN), European Union (EU), Food and Agriculture Organization of the UN (FAO), Organisation for Economic Co-operation and Development and World Bank (2014). System of Environmental-Economic Accounting 2012: Experimental Ecosystem Accounting.

[6] The WAVES Partnership, initiated by the World Bank, is seeking to establish environmental and more experimental ecosystem accounts following the SEEA in partner countries and incorporate these into national policy analysis and development planning. :

[7] See gov.uk's Air quality: economic analysis article.

While the methodology employed provided reasonable estimates, the final report recommended a number of ways in which the methodology could be further refined and extended. These included:

- developing estimates for other pollutants and in particular for SO_2 for which there is good data available[8]
- better accounting for the impact of population density on the value of this service and the difference between rural and urban habitats
- estimating time series change in the provision of this service

This project aims to draw on this approach to develop a replicable methodology to account for the value of natural capital in absorbing air pollution at a UK level. Specifically, the methodology is expected to result in:

- estimates of the physical and monetary flows of air quality regulation provided by the UK's natural capital
- estimates of the asset value of this natural capital based on projected service flows

The methodology builds on the earlier work conducted by AECOM on developing experimental ecosystem accounts for Defra and will aim to answer the following questions:

- question 1: How much PM_{10} and SO_2 was absorbed by the UK's natural capital in 2012 and what was the value of this service?[9]
- question 2: How do the results compare to the i-Tree assessment 'Valuing London's Urban Forest'?
- question 3: How did the quantity and value of this service change over the period 2006 and 2012?[10]
- question 4: How do the estimates of PM_{10} and SO_2 absorption differ across the Corine and Land Cover Map datasets?

[8] Note, there are a number of other important pollutants in the UK including NO_X, ozone, and ammonia. While it is recognised that a more complete understanding of pollution absorption would require quantification of the absorption of these pollutants, it was not possible in this project due to a lack of available dose-response relationships. The two pollutants for which such relationships are available were PM_{10} and SO_2.

[9] Note, 2012 was chosen as the base year as this is the most recent year for which full UK wide habitat mapping is available through the Corine 2012 habitat map. Corine data was selected over LCM data due to the greater consistency of habitat estimates between years in the Corine approach. Further the Corine data is publically accessible and assessments are planned to be undertaken with regularity into the future.

[10] Note, 2006 was chosen as a comparison year as this is the most recent iteration of the Corine habitat map undertaken prior to 2012.

Methodology

Physical flows

The approach to quantifying the physical flows of air quality regulation services provided by natural capital in the UK was based on the model set out in Powe and Willis (2004)[11]. According to this model, the rate of pollution absorption by different habitat types can be estimated using the following formula:

ABSORPTION = FLUX x SURFACE x PERIOD

Where:

FLUX = deposition velocity (m/s) x pollutant concentration (µg/m^3)

SURFACE = surface area index (m^2 per m^2 of ground area) x area of land considered (m^2)

PERIOD = period of analysis (days) x proportion of dry days (fraction) x proportion of on-leaf days (fraction)

The following sections set out the approach taken to calculate each step of this formula.

A. Habitat mapping

The underlying habitat mapping data was based on the Corine 2012 dataset (using the British National Grid projection)[12] which was obtained from the Centre for Ecology and Hydrology (CEH). The Corine 2012 data had an accompanying changes dataset containing polygons with corrected habitat codes; these changes were applied to the downloaded 2012 data to create a revised version used in the analysis. A unique identifier was assigned to each 1x1 km square of the UK to enable the Corine 2012 land cover data and the changes dataset to be compared in each grid square.

B. Estimating FLUX

The next step was to cross reference the Corine habitat classification system with that used by Powe and Willis (2004).[13] The assumed overlap, based on professional judgement, between the habitat classification systems is set out in Appendix 1. Each grid square was then assigned a deposition velocity for on-leaf and off-leaf periods based on the habitat type within the square. The deposition rates were drawn from Powe and Willis (2004)[14] and are set out in Table 1.

Table 1. Deposition velocities for different habitat types for the UK, 2012

[11] Powe and Willis (2004), 'Mortality and morbidity benefits of air pollution (SO2 and PM10) absorption attributable to woodland in Britain', Journal of Environmental Management, 70, 119-128.

[12] Cole, B.; King, S.; Ogutu, B.; Palmer, D.; Smith, G.; Balzter, H. (2015). 'Corine land cover 2012 for the UK, Jersey and Guernsey'. NERC Environmental Information Data Centre. doi:10.5285/32533dd6-7c1b-43e1-b892-e80d61a5ea1d

[13] Powe and Willis (2004), 'Mortality and morbidity benefits of air pollution (SO2 and PM10) absorption attributable to woodland in Britain', Journal of Environmental Management, 70, 119-128.

[14] Powe and Willis (2004), 'Mortality and morbidity benefits of air pollution (SO2 and PM10) absorption attributable to woodland in Britain', Journal of Environmental Management, 70, 119-128.

Habitat type (Powe and Willis)	On-leaf deposition velocity (m/s)		Off-leaf deposition velocity (m/s)	
	PM_{10}	SO_2	PM_{10}	SO_2
Coniferous	0.0080	0.0008	0.0080	0.0008
Deciduous	0.0050	0.0005	0.0014	0.0001
Heather or grass	0.0010	0.0002	0.0010	0.0001
No vegetation	0.0000	0.0000	0.0000	0.0000

Source: AECOM

The background pollution concentration in 2012 was then calculated for each grid square based on data provided by Defra.[15] The definition and method for quantifying background pollution concentration is set out in Ricardo-AEA (2015).[16] Background pollution concentration was multiplied by deposition velocity and the units were converted to kg per m^2 per day to estimate FLUX for on-leaf and off-leaf periods.

C. Estimating SURFACE

Estimates of the surface area index of vegetation for different habitat types in on-leaf and off-leaf periods were drawn from the Powe and Willis (2004)[17] study and are set out in Table 2. The surface area indices were then multiplied by the area of each habitat within each grid square in 2012 to estimate SURFACE in terms of m^2 for on-leaf and off-leaf periods.

Table 2. Surface area indices

Habitat type (Powe and Willis)	Surface area index (m^2 per m^2 of ground)	
	On-leaf	Off-leaf
Coniferous	9.0	9.0
Deciduous	6.0	1.7
Heather or grass	2.0	1.5
No vegetation	0.0	0.0

Source: Powe and Willis, 2004

D. Estimating PERIOD

The period of analysis was assumed to be 365 days. Of these, the proportion of “dry” days (defined as days in which

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[15] Defra (2015), ‘Background pollution maps at 1x1 km resolution are modeled each year under Defra's Ambient Air Quality Assessments (UKAAQA) contract’.

[16] Ricardo AEA (2015), Technical report on UK supplementary assessment under the Air Quality Directive (2008/50/EC), the Air Quality Framework Directive (96/62/EC) and Fourth Daughter Directive (2004/107/EC) for 2013.

[17] Powe and Willis (2004), ‘Mortality and morbidity benefits of air pollution (SO2 and PM10) absorption attributable to woodland in Britain’, Journal of Environmental Management, 70, 119-128.

rainfall was less than 1 mm) for each region in 2012 was estimated by data from the Met Office[18] and is summarised in Table 3. This approach therefore focused on dry deposition and assumed there is no deposition during wet days.

Table 3. Proportion of dry days in the UK by region, 2012

Region	Number of days in 2012 when rainfall exceeded 1 mm (days)	Proportion of "dry" days in 2012 (%)
East of England	148.2	59.40%
East Midlands	153.6	57.92%
Isle of Man	185.9	49.07%
London	140.9	61.40%
North East	148.2	59.40%
North West	185.9	49.07%
Northern Ireland	183.7	49.67%
Scotland	195.2	46.52%
South East	140.9	61.40%
South West	179.9	50.71%
Wales	190.8	47.73%
West Midlands	153.6	57.92%
Yorkshire and Humber	148.2	59.40%

Source: Met Office

The proportion of on-leaf relative to off-leaf days was estimated for the UK as a whole, based on an estimate of the average number of bare leaf days for five of the most common broadleaf tree species in the UK, that is, ash, beech, horse chestnut, English oak, and silver birch. This was estimated for 2012 based on the UK-wide difference between the day of budding and the day of becoming bare.[19] The total number of days of on-leaf and off-leaf air pollution absorption was then estimated by multiplying these 3 factors together to estimate the PERIOD in days.

E. Estimating TOTAL

On-leaf and off-leaf pollution absorption was then estimated by multiplying FLUX, SURFACE, and PERIOD. These were then added together to estimate the TOTAL kg of PM_{10} and SO_2 absorbed by habitats within each grid square in 2012. This was then converted into tonnes of pollution absorbed for each grid square. The results were then aggregated across the broad habitat types used by the UK national ecosystem assessment (NEA) to facilitate our reporting (see Appendix 1 for the assumed overlaps between different habitat classification types).

[18] Met Office (2016), 'Download regional values'.

[19] Woodland Trust (2016), 'Table of averages'.

Monetary flows

A. Estimating the annual value of pollution absorption

The approach to valuing the air quality regulation service provided by the UK's natural capital was based on guidance set out by Defra which provides a set of standardised estimates of the damage costs per tonne of emissions for several pollutants, including PM_{10} and SO_2, across the UK.[20]

Using these estimates, it was assumed that the value of each tonne of pollutant absorbed by natural capital is equal to the average damage cost of that pollutant. Note that these social damage costs are based on avoided mortality and morbidity rather than damages in a physical sense.

For emissions of SO_2, the average damage cost is estimated to be £1,956 across all locations in 2015. However, a range of damage cost estimates are provided for PM_{10} emissions depending on the location and source of pollution. In order to account for some of the spatial variation in damage costs, the percentage of each grid square located within an "urban" area was identified using the following datasets:

- England and Wales – rural and urban classification of output areas 2011 sourced from the Office for National Statistics Geoportal. Output areas are treated as 'urban' if they were allocated to a built-up area with a population of 10,000 or more (as of 2011).

- Scotland – urban and rural classification for 2013 to 2014 sourced from the Scottish government website. The classification was provided in 3 tiers; the most basic tier of urban/rural was selected.

- Northern Ireland – urban-rural classification 2005 sourced from Northern Ireland Statistics and Research Agency (NISRA). These areas are defined from settlement development limits (SDLs) which are a statistical classification and delineation of settlements. A review of the urban or rural classifications was undertaken and an initial report was published in 2015 which makes recommendations about new classifications. The revised set of boundaries is, however, yet to be released.

Using this classification system, each grid square was classified as "urban", "rural", or"London". An average damage cost for PM_{10} emissions in 2015 (assumed to be from transport sources) was then estimated (see Table 4). Note, these damage costs cover all PM not just PM_{10}.

Table 4. Defra UK damage costs by pollutant location in 2015 (2015 prices)[21]

Location	PM_{10} damage cost (£ per tonne)
Central London	£265,637
Inner London	£273,193
Outer London	£178,447
London average	£239,092
Inner conurbation	£141,248
Outer conurbation	£87,770

[20] Defra (2015) 'Air quality: economic analysis'.

[21] Defra (2015) 'Damage costs by location and source'

Location	PM_{10} damage cost (£ per tonne)
Urban big	£104,627
Urban large	£84,283
Urban medium	£66,264
Urban small	£41,850
Urban average	£77,723
Rural	£18,020
Rural average	£18,020

Source: Defra

The average damage costs for PM_{10} and SO_2 in 2015 were then deflated by 2% each year to estimate the average damage costs in 2012, in order to reflect the assumption that willingness to pay for health rises and falls in line with economic growth.[22] The final values used in the calculation were therefore:

- rural PM_{10} = £16,960.28
- urban PM_{10} = £73,152.27
- London PM_{10} = £225,031.48
- SO_2 = £1,840.97

These values were then multiplied by the total absorption of PM_{10} and SO_2 by habitats within each grid square to estimate the total value of pollution regulation within the square.

B. Estimating the asset value of natural capital

The asset value of the UK's natural capital was also estimated in terms of its ability to provide air quality regulation services into the future. The asset value was estimated over a 50-year period using the discount rates provided in HM Treasury's Green Book[23] and the formula:

$$Asset\ value = \sum_{t=0}^{n} \frac{unit\ value\ in\ year\ t}{(1+r)^t}$$

The unit value was assumed to be constant over the 50-year period and equal to the unit value in 2012.

[22] Defra (2011), 'Air quality damage cost guidance'.

[23] HM Treasury (2011), 'The Green Book'.

Results

How much PM_{10} and SO_2 was absorbed by the UK's natural capital in 2012 and what was the value of this service?

Summary of results

The results of the analysis suggest:

- the level of dry deposition on the UK's natural capital in 2012 was around 220,000 tonnes of PM_{10} and 2,800 tonnes of SO_2
- most deposition occurred on woodland habitats, both in absolute terms and in terms of the amount absorbed relative to the total area of the habitat across the UK
- the total value of the PM_{10} absorbed was estimated to be around £4.5 billion, while the value for SO_2 was £5.2 million
- the asset value of the UK's natural capital in terms of its ability to provide this service over the next 50 years was estimated to be around £114.1 billion for PM_{10} and £134.0 million for SO_2
- rural areas were estimated to account for around 80% of the value of PM_{10} absorption although the average value of PM_{10} absorption in a rural grid square (£6,000) was much lower than in an urban (£13,000) or London grid square (£24,000) due to the higher population densities and therefore higher damage costs in urban areas
- for SO_2, rural areas were estimated to account for around 92% of the value and the average value in a rural grid square (£8) was higher than in an urban (£7) or London grid square (£3) since the damage cost estimates for SO_2 do not account for population density

Note that these estimates are subject to a number of sources of uncertainty which are reflected in the assumptions around habitat cover, deposition rates, and damage costs. These are discussed in the limitations and further research section.

Full results

Estimates of the total absorption of PM_{10} and SO_2 by natural capital in 2012 based on Corine 2012 data are set out in Table 5.

Table 5. Quantity of PM_{10} and SO_2 absorbed by natural capital in the UK in 2012 using Corine 2012

Habitat type (UK NEA)	PM_{10} absorbed		SO_2 absorbed	
	Total (tonnes)	Average (tonnes/km^2)	Total (tonnes)	Average (tonnes/km^2)
Woodland	151,818	7.055	1,452	0.071
Enclosed farmland	54,919	0.395	1,159	0.008

Semi-natural grassland	5,795	0.282	109	0.005
Open water, wetland, and floodplain	5,034	0.198	58	0.002
Mountain, moorland, and heath	4,196	0.198	63	0.003
Coastal margin	163	0.173	4	0.004
Urban[24]	0	0.000	0	0.000
Marine	0	0.000	0	0.000
TOTAL	221,925	0.790	2,845	0.010

Source: AECOM

Estimates of the value of PM_{10} and SO_2 absorption by natural capital in 2012 based on Corine 2012 data are set out in Table 6.

Table 6. Value of PM_{10} and SO_2 absorbed by natural capital in the UK in 2012 using Corine 2012 data

Habitat type (UK NEA)	Annual value PM_{10} (£)	Asset value PM_{10} (£)	Annual value SO_2 (£)	Asset value SO_2 (£)
Woodland	£3.0 billion	£75.9 billion	£2.7 million	£68.4 million
Enclosed farmland	£1.2 billion	£29.8 billion	£2.1 million	£54.6 million
Semi-natural grassland	£0.16 billion	£4.2 billion	£0.20 million	£5.1 million
Open water, wetland, and floodplain	£0.09 billion	£2.3 billion	£0.11 million	£2.7 million
Mountain, moorland, and heath	£0.08 billion	£1.9 billion	£0.12 million	£2.9 million
Coastal margin	£0.004 billion	£0.10 billion	£0.01 million	£0.20 million
Urban	£0	£0	£0	£0
Marine	£0	£0	£0	£0
TOTAL	£4.5 billion	£114.1 billion	£5.2 million	£134.0 million

Source: AECOM

A comparison of the value of PM_{10} and SO_2 absorption in the rural, urban, and London areas is set out in Table 7. In addition to the total value of pollution absorption in each area type, a comparison is also provided of the value of

[24] Note, urban habitat types by definition have zero vegetation cover and are therefore assumed to have a pollution absorption rate of 0. Vegetated habitats located within urban areas (for example, parks, trees, and open waters) are recorded in the relevant habitat type (for example, semi-natural grasslands, woodlands, and open waters, wetlands and floodplains).

pollutant absorption relative to the number of grid squares of each type.

Table 7. Comparison of the value of PM_{10} and SO_2 absorption in rural, urban, and London areas

Classification	PM_{10} absorption		SO_2 absorption	
	Total value of PM_{10} absorption (£)	Value relative to number of grids (£/1km^2 grid)	Total value of SO_2 absorption (£)	Value relative to number of grids (£/1km^2 grid)
Rural	£3.6 billion	£5,959	£4.8 million	£8.00
Urban	£0.79 billion	£12,695	£0.43 million	£6.92
London	£0.10 billion	£24,339	£0.01 million	£2.71

Source: AECOM

Pollution is absorption is greater than the amount recorded in emissions – why?

It is important to note that the estimated quantity of PM_{10} absorbed is higher than Defra's and our own statistics on total annual emissions of PM_{10}, while that for SO_2 is lower. For example, ONS estimate that total PM_{10} emissions in 2012 were 170,000 tonnes while SO_2 emissions were 563,000 tonnes.

The reason that the estimates of PM_{10} absorption are higher than the estimated emissions appears to be due to the fact that the Defra emissions statistics do not fully account for natural or secondary sources of PM_{10}. The Defra emissions statistics include the following sources of emissions:

- energy industries
- manufacturing industries and construction
- road transport
- non-road transport
- other sectors
- other, mobile (including military)
- fugitive emissions
- industrial processes
- agriculture
- waste
- other

The dataset also estimates "memo items" of around 34,000 tonnes of PM_{10} and 72,000 tonnes of SO_2 in 2013. While these are estimated in the document they are not included in the reported totals, as such the "total" emissions according to this dataset would be closer to 179,000 tonnes of PM_{10} and 512,000 tonnes of SO_2. According to the Defra dataset these memo items include the following sources:

- international and national aircraft (cruise)
- international shipping
- forest fires
- natural emissions
- NH_3 emissions from wild animals and humans, and anaerobic digestion

From a review of the literature it appears that these memo items are smaller than would typically be expected. For example, Aleksandropoulou and others suggest that the share of natural and secondary sources of PM_{10} can be up to 79%.[25] This suggests that some of these emissions sources may not be reported in the Defra dataset. This inference is supported when looking at the Defra background PM_{10} dataset from which the model draws.[26] This data includes the following sources:

- secondary inorganic aerosol
- secondary organic aerosol
- large point sources of primary particles
- small point sources of primary particles
- point sources with emissions estimates for air quality pollutants based on reported carbon emissions (ETS points)
- regional primary particles
- area sources related to domestic combustion
- area sources related to combustion in industry
- area sources related to road traffic
- other area sources
- regional calcium rich dusts from re-suspension of soils
- urban calcium rich dusts from re-suspension of soils due to urban activity
- regional iron rich dusts from re-suspension
- iron rich dusts from re-suspension due to vehicle activity
- sea salt

[25] Aleksandropoulou and others. (2015) Contribution of Natural Sources to PM Emissions over the Metropolitan Areas of Athens and Thessaloniki, Aerosol and Air Quality Research, 15: 1300 1312, 2015.

[26] Defra (2015), 'Technical report on UK supplementary assessment under the Air Quality Directive (2008/50/EC), the Air Quality Framework Directive (96/62/EC) and Fourth Daughter Directive (2004/107/EC) for 2013'.

- residual

According to this analysis, the emissions sources which are captured in the estimates of total pollutant emissions are much smaller than the “natural” or “secondary” emissions.

By contrast, estimates of the level of SO_2 absorption are much lower than the recorded emissions. This is again likely to be due to a difference in the methods used for quantifying pollutant emissions and background concentrations in the relevant Defra datasets. For example, while the Defra emissions data suggests that SO_2 emissions (440,000 tonnes in 2012) are much higher than PM_{10} emissions (145,000 tonnes in 2012), the background pollution dataset suggests that SO_2 concentrations (average background concentration of 1.2 µg/m^3 in 2012) are much lower than those for PM_{10} (average background concentration of 10.3 µg/m^3 in 2012).

How do the results compare to the i-Tree assessment 'Valuing London's Urban Forest'?

The results of the model were then compared against the results of the 2015 i-Tree assessment Valuing London's Urban Forest. The comparison was made by identifying each of the 1x1 km grids located within the Greater London Area and running the Corine 2012 model for this particular area.

Summary of results

The results of the analysis suggest:

- estimates of the total amount of PM_{10} absorbed within the Corine 2012 model were higher than the i-Tree 2015 model as the latter did not consider absorption by grassland habitats in addition to trees
- when focusing on the amount of PM_{10} absorbed by trees only (rather than across all habitat types) the results were comparable across the Corine 2012 and i-Tree 2015 models, although the Corine 2012 estimates were slightly lower
- estimates of the total amount of SO_2 absorbed using the Corine 2012 model are lower than the i-Tree 2015 model both when looking at all habitats and when focusing specifically on trees. This may be due to the fact that the model assumed wet deposition was equal to zero when in reality, wet deposition for SO_2 can be up to 1.5 times that of dry deposition

Full results

According to the i-Tree assessment, trees in the Greater London area absorbed 299 tonnes of PM_{10} in 2015 and 62 tonnes of SO_2. The total amount of pollutant absorption estimated in the Corine 2012 model across all habitats (including woodlands, semi-natural grassland (SNG), open water, wetland, and floodplain (OWWF), and mountain, moorland and heath (MMH) habitats) is set out in Table 8.

Since the i-Tree 2015 model only estimates pollution absorbed by trees and does not therefore include grassland or other habitats, a comparison is also provided which focuses on the amount of pollution absorbed by trees in woodland habitats. This is lower than the i-Tree assessment for both PM_{10} and SO_2, which may be due to the coarser spatial resolution of Corine failing to pick up small areas of trees within the London area (see Section 4.1).

However, estimates of the total amount of SO_2 absorbed using the Corine 2012 model are lower than the i-Tree 2015 model both when looking at all habitats and when focusing specifically on trees. This may be due to the fact that the model assumed wet deposition was equal to zero when in reality, wet deposition for SO_2 can be up to 1.5 times that of dry deposition, meaning that only about 40% of the SO_2 deposition is captured in this model (see Section 4.1).[27]

Table 8. Comparison of the estimates of pollution absorbed in the Greater London area

Model	Pollution absorption across all habitats		Pollution absorption by trees	
	PM_{10} (tonnes)	SO_2 (tonnes)	PM_{10} (tonnes)	SO_2 (tonnes)
Corine 2012	457	6	203	2

[27] Pers. Comm. CEH, 2016

i-Tree 2015	299	62	299	62
Difference	**158**	**-56**	**-96**	**-60**

Source: AECOM

How did the quantity and value of this service change over the period between 2006 and 2012?

Methodology

In order to compare the flow of air quality regulation services in 2006 and 2012, the model was also run using Corine 2006 habitat data. The Corine 2006 model was developed using each of the steps described in the methodology section, although datasets specific to 2006 were used for the following variables:

- the extent of habitat within each grid square
- the background pollution concentrations – for comparison, average background pollution concentrations in 2006 were 11.30 μg/m^3 for PM_{10} and 1.51 μg/m^3 for SO_2, while in 2012 they were 10.27 μg/m^3 for PM_{10} and 1.22 μg/m^3 for SO_2
- the proportion of dry days – the proportion of dry days varied by region, with the average being 59% in 2006 and 55% in 2012
- the proportion of on-leaf relative to off-leaf days – this factor varied from 60% in 2006 to 61% in 2012
- the damage cost of pollution (this was deflated 2% each year from the 2015 value provided by Defra)

The approach to classifying each grid square as urban, rural, or London was assumed to be the same in both the 2006 and 2012 model, although future versions could potentially consider urban expansion where information is available.

Summary of results

The results of the analysis suggest:

- According to the Corine datasets, the total area of woodland across the UK decreased by around 4% from 2006 to 2012, this was largely offset by a corresponding increase in the area of semi-natural grassland
- the level of dry deposition of PM_{10} was 21% lower in 2012 while that for SO_2 was 29% lower based on a decrease in woodland cover, differences in background pollution concentrations, and a decrease in the number of dry days; the higher number of on-leaf days in 2012 and the spatial configuration of habitat (for example, how much woodland is located in urban relative to rural habitats) may also explain some of the differences between the two years
- the value of PM_{10} absorbed was 11% lower in 2012 while that for SO_2 was 20% lower. This may be explained by differences in the area of land cover, spatial configuration of habitats, background pollution concentration, the proportion of dry and on-leaf days, and the willingness-to-pay for healthcare (and thereby deflation of the unit damage cost)

Note that while the comparison suggests that there has been a decline in the absorption of both PM_{10} and SO_2, this does not necessarily imply a decreasing trend. This is because there are a number of other factors that may have influenced the levels of deposition and absorption in each of the years compared. For example, 2006 was an abnormal year – very hot and dry, which caused an increase in atmospheric pollutant concentration due to reduced stomatal uptake, while 2012 was a comparatively wet year.

Full results

The change in the total area of each habitat type between 2006 and 2012 is set out in Table 9.

Table 9. Area of habitat type in the UK in 2006 and 2012 using Corine 2006 and 2012 data

Habitat type (UK NEA)	Total area in 2006 (km^2)	Total area in 2012 (km^2)	Change in area	
			km^2	%
Woodland	21,520	20,558	-962	-4.47%
Enclosed farmland	139,108	138,961	-147	-0.11%
Semi-natural grassland (SNG)	20,530	21,454	924	4.50%
Open water, wetland, and floodplain (OWWF)	25,486	25,491	5	0.02%
Mountain, moorland, and heath (MMH)	21,190	21,191	1	0.00%
Coastal margin	943	942	-1	-0.11%
Urban	16,951	17,130	179	1.06%
Marine	35,099	35,100	1	0.00%
TOTAL	280,827	280,827	0	0.00%

Source: AECOM

The change in the quantity of pollution absorption between 2006 and 2012 is set out in Table 10. The differences between the estimates are based on changes in the area of land cover, spatial configuration of habitats, background pollution concentration, and the proportion of dry and on-leaf days.

Table 10. Quantity of PM_{10} and SO_2 absorbed by natural capital in the UK in 2006 and 2012 using Corine 2006 and 2012 data

Habitat type (UK NEA)	PM_{10} absorbed (tonnes)				SO_2 absorbed (tonnes)			
	2006	2012	Change (tonnes)	Change (%)	2006	2012	Change (tonnes)	Change (%)
Woodland	197,548	151,818	-45,731	-23.15%	2,130	1,452	-678	-31.83%
Enclosed farmland	64,763	54,919	-9,846	-15.20%	1,567	1,159	-408	-26.04%
SNG	6,990	5,795	-1,195	-17.10%	147	109	-38	-25.85%
OWWF	5,926	5,034	-892	-15.05%	75	58	-17	-22.67%
MMH	5,082	4,196	-886	-17.43%	86	63	-23	-26.74%
Coastal margin	198	163	-35	-17.68%	4	4	0	0.00%
Urban	0	0	0	0	0	0	0	0

Marine	0	0	0	0	0	0	0	0
TOTAL	280,507	221,925	-58,585	-20.89%	4,009	2,845	-1,164	-29.03%

Source: AECOM

A comparison of the key factors underlying the differences in absorption values between the years 2006 and 2012 is set out in Table 11. Urban and marine habitats have been excluded as pollution deposition to each habitat was estimated to be zero.

Note that the spatial configuration of habitat (for example, how much woodland is located in urban relative to rural habitats) is also likely to be a factor, although it was beyond the scope of this project to quantify the change between the two datasets.

Table 11. Comparison of factors underlying 2006 and 2012 UK pollution absorption estimates

Breakdown by all habitats can be given on request

Factor	2006	2012	Change (units)	Change (%)
All habitats				
Total area (km^2)	280,827	280,827	0	0.00%
Average background SO_2 concentration ($\mu g/m^3$)	1.51	1.22	-0.29	-19.01%
Average background PM_{10} concentration ($\mu g/m^3$)	11.30	10.27	-1.03	-9.12%
Number of on-leaf days	220	222	2	0.90%
Average number of dry days	217	199	-18	-8.29%
Woodland				
Total area (km^2)	21,520	20,558	-962	-4.47%
Average background SO_2 concentration ($\mu g/m^3$)	1.47	1.15	-0.32	-21.77%
Average background PM_{10} concentration ($\mu g/m^3$)	11.87	10.53	-1.34	-11.29%
Number of on-leaf days	220	222	2	0.91%
Average no. of dry days	203	187	-16	-7.88%

Source: AECOM

The difference in the annual and asset value of pollution absorption between 2006 and 2012 is set out in Table 12 and Table 13 respectively. The differences between the estimates are based on changes in the area of land cover, spatial configuration of habitats, background pollution concentration, the proportion of dry and on-leaf days, and the willingness-to-pay for healthcare (and thereby deflation of the unit damage cost).

Table 12. Annual value of PM_{10} and SO_2 absorbed by natural capital in the UK in 2006 and 2012, using Corine 2006 and 2012 data

Habitat type (UK NEA)	Annual value of PM_{10} absorbed (£)			
	2006	2012	Change (£)	Change (%)
Woodland	£3.4 billion	£3.0 billion	-£0.48 billion	-13.89%
Enclosed farmland	£1.2 billion	£1.2 billion	-£0.07 billion	-5.34%
SNG	£0.18 billion	£0.16 billion	-£0.02 billion	-9.81%
OWWF	£0.09 billion	£0.09 billion	-£0.004 billion	-4.17%
MMH	£0.08 billion	£0.08 billion	-£0.01 billion	-7.45%
Coastal margin	£0.004 billion	£0.004 billion	-£0.0003 billion	-6.59%
Urban	£0	£0	£0	0%
Marine	£0	£0	£0	0%
TOTAL	£5.0 billion	£4.5 billion	-£0.57 billion	-11.37%
Habitat type (UK NEA)	**Annual value of SO_2 absorbed (£)**			
	2006	**2012**	**Change (£)**	**Change (%)**
Woodland	£3.5 million	£2.7 million	-£0.80 million	-23.03%
Enclosed farmland	£2.6 million	£2.1 million	-£0.42 million	-16.53%
SNG	£0.24 million	£0.20 million	-£0.04 million	-16.31%
OWWF	£0.12 million	£0.11 million	-£0.02 million	-12.55%
MMH	£0.14 million	£0.12 million	-£0.03 million	-17.84%
Coastal margin	£0.01 million	£0.01 million	£0.001 million	21.13%
Urban	£0	£0	£0	0%
Marine	£0	£0	£0	0%
TOTAL	£6.5 million	£5.2 million	-£1.3 million	-19.89%

Source: AECOM

Table 13. Asset value of PM_{10} and SO_2 absorbed by natural capital in the UK in 2006 and 2012 using Corine 2006 and 2012 data

Habitat type (UK NEA)	Asset value of PM_{10} absorbed (£)			
	2006	2012	Change (£)	Change (%)
Woodland	£88.1 billion	£75.9 billion	-£12.2 billion	-13.89%
Enclosed farmland	£31.5 billion	£29.8 billion	-£1.7 billion	-5.34%
SNG	£4.6 billion	£4.2 billion	-£0.45 billion	-9.81%
OWWF	£2.4 billion	£2.3 billion	-£0.10 billion	-4.17%
MMH	£2.1 billion	£1.9 billion	-£0.16 billion	-7.45%
Coastal margin	£0.11 billion	£0.10 billion	-£0.01 billion	-6.59%
Urban	£0	£0	£0	0%
Marine	£0	£0	£0	0%
TOTAL	£128.8 billion	£114.1 billion	-£14.6 billion	-11.37%
Habitat type (UK NEA)	**Asset value of SO_2 absorbed (£)**			
	2006	**2012**	**Change (£)**	**Change (%)**
Woodland	£88.8 million	£68.4 million	-£20.5 million	-23.03%
Enclosed farmland	£65.4 million	£54.6 million	-£10.8 million	-16.53%
SNG	£6.1 million	£5.1 million	-£1.0 million	-16.31%
OWWF	£3.1 million	£2.7 million	-£0.39 million	-12.55%
MMH	£3.6 million	£2.9 million	-£0.64 million	-17.84%
Coastal margin	£0.16 million	£0.20 million	£0.03 million	21.13%
Urban	£0	£0	£0	0%
Marine	£0	£0	£0	0%
TOTAL	£167.2 million	£134.0 million	-£33.3 million	-19.89%

Source: AECOM

Woodland estimates compared with Forestry Commission data

According to the Corine datasets, the total area of woodland across the UK decreased by around 4% from 2006 to 2012; this was largely offset by a corresponding increase in the area of semi-natural grassland. However, the difference in woodland cover recorded in the Corine datasets appears contrary to statistics provided by the Forestry Commission (FC) which suggest an increase in woodland habitat over this period.[28]

[28] Forestry Commission (2015), 'Forestry Statistics 2015'.

To investigate this issue further an analysis was undertaken of the changes in woodland habitat between the two Corine datasets. The results suggest that the decrease in woodland cover was largely due to the felling of coniferous woodland habitats (see Table 14). Following clear felling, these habitats were then typically classified as "transitional woodland-shrub" which were classified as semi-natural grassland habitats in the model. In some cases these habitats were converted for development and classified as "industrial" habitats or "urban" in the model (see Appendix 1).

Table 14. Change in woodland cover between Corine 2006 and Corine 2012 datasets

Habitat	Area in 2006 (ha)	Area in 2012 (ha)	Change (ha)	Change (%)
Broadleaved forest	534,503	534,887	384	0.07%
Coniferous forest	1,344,104	1,251,049	-93,055	-6.92%
Mixed forest	273,435	269,887	-3,548	-1.30%
All woodland	2,152,042	2,055,823	-96,219	-4.47%

These findings are supported by an analysis from the University of Leicester which suggests that the dominant change in habitats between the two periods was the clear-cutting of over 100,000 hectares of coniferous forest and the clearance of around 3,000 hectares of coniferous forests for industrial development.[29]

The observed difference in woodland changes statistics between the FC and Corine datasets is likely to be due to the different definitions of woodland used in the two approaches. The Corine dataset is based on areas of land that resemble woodland habitats on satellite imagery, as in, areas which are covered in trees. The FC, on the other hand, defines woodland as follows:

> "Land under stands of trees with a canopy cover of at least 20% (25% in Northern Ireland), or having the potential to achieve this. The definition relates to land use, rather than land cover, so integral open space and felled areas that are awaiting restocking are included as woodland."[30]

In light of this, the difference between the FC and the Corine datasets is likely due to the fact that the FC classifies the 100,000 hectares of clear felled coniferous woodland as "woodland" as it has the potential to grow back, while Corine classes this area as "transitional woodland-shrub". The FC also classes any newly planted broadleaved woodland as woodland, while Corine classes this area as "transitional woodland-shrub". So, according to the FC figures, there is a net increase of woodland broadly equivalent to the planted area, whereas Corine records show a net decrease in woodland as it accounts for the clear felled area as a loss of woodland and does not pick up the increase associated with any newly planted woodland.

Given that recently felled or newly planted woodland is unlikely to have the pollution absorption capacity of fully established woodland, it is suggested that the Corine data provides a more useful approach for this modelling exercise.

[29] University of Leicester (2015) 'State of our countryside: Land use map of the United Kingdom reveals large-scale changes in environment'

[30] Forestry Commission (2015), 'Forestry Statistics 2015',

How do the estimates of PM_{10} and SO_2 absorption differ across the Corine and land cover map datasets?

The model was also run using the 2007 land cover map (LCM) data as the underlying measure of the extent of habitat within each grid square across the UK. The LCM 2007 data was supplied in raster format because Northern Ireland was not available in vector format; the resolution of the raster data was deemed to be acceptable. Datasets were projected in British national grid and split into 1x1 km grid squares, each of which were given a unique identifier allowing comparison. Each step in the methodology was the same as set out above, and values for 2006 were used to allow comparison with the Corine 2006 model. The assumed overlaps between habitat classifications are set out in the next section.

Summary of results

There were significant differences in the area of different habitat types across the two datasets, with Corine 2006 recording around 34% less woodland cover than LCM 2007.

The level of dry deposition of PM_{10} and SO_2 was around 18% lower in Corine 2006 based on differences in the area of land cover and the spatial configuration of habitats.

The value of PM_{10} absorbed was around 24% lower in the Corine 2006 model while that for SO_2 was around 18% based on differences in the area of land cover and the spatial configuration of habitats.

Full results

The difference in the total area of each habitat type between the Corine and LCM datasets is set out in Table 15. The Corine dataset contains a buffer of marine habitat around the entire UK landmass which is not included within the LCM dataset. As such, Corine records a significantly higher area of marine habitat than LCM. If marine habitats are excluded the total land area is similar across the two datasets.

Table 15. Comparison of the area of each habitat type in the UK using Corine 2006 and LCM 2007 datasets

Habitat type (UK NEA)	Total area in Corine 2006 (km^2)	Total area in LCM 2007 (km^2)	Difference in area	
			km^2	%
Woodland	21,520	28,783	-7,263	-33.75%
Enclosed farmland	139,108	125,357	13,751	9.89%
Semi-natural grassland (SNG)	20,530	32,729	-12,199	-59.42%
Open water, wetland, and floodplain (OWWF)	25,486	14,343	11,143	43.72%
Mountain, moorland, and heath (MMH)	21,190	27,353	-6,163	-29.08%
Coastal margin	943	1,002	-59	-6.26%
Urban	16,951	14,648	2,303	13.59%

Marine	35,099	4,119	30,980	88.26%
TOTAL	280,827	248,334	32,493	11.57%
TOTAL (exc. Marine)	245,728	244,215	1,513	0.62%

The difference in physical flows of pollution absorption between the two datasets is set out in Table 16. The difference in estimates is due to differences in the area of land cover and the spatial configuration of habitats. All other factors (as in, background pollution concentration, and the proportion of dry and on-leaf days) are the same across both models.

Table 16. Comparison of PM_{10} and SO_2 absorbed by natural capital in the UK using Corine 2006 and LCM 2007 data

Habitat type (UK NEA)	PM_{10} absorbed (tonnes)				SO_2 absorbed (tonnes)			
	Corine 2006	LCM 2007	Difference (tonnes)	Difference (%)	Corine 2006	LCM 2007	Difference (tonnes)	Difference (%)
Woodland	197,549	251,165	-53,616	-27.14%	2,130	2,897	-767	-36.01%
Enclosed farmland	64,765	59,613	5,152	7.95%	1,567	1,468	99	6.32%
SNG	6,990	10,906	-3,916	-56.02%	147	214	-67	-45.58%
OWWF	5,926	3,006	2,920	49.27%	75	41	34	45.33%
MMH	5,082	6,808	-1,726	-33.96%	86	105	-19	-22.09%
Coastal margin	198	183	15	0%	4	4	0	0%
Urban	0	0	0	0%	0	0	0	0%
Marine	0	0	0	0%	0	0	0	0%
TOTAL	**280,510**	**331,680**	-51,170	-18.24%	**4,009**	**4,728**	**-719**	**-17.93%**

Source: AECOM

The difference in monetary flows of pollution absorption between the two datasets is set out in Table 17 (annual values) and Table 18 (asset values). The differences between the estimates can be explained entirely by changes in the area of land cover and the spatial configuration of habitats. All other factors are the same, including background pollution concentration, the proportion of dry and on-leaf days, the willingness-to-pay for healthcare (and thereby deflation of the unit damage cost), and the classification of rural and urban areas.

Table 17. Comparison of annual value of PM_{10} and SO_2 absorbed by natural capital in the UK using Corine 2006 and LCM 2007 data

Habitat type (UK NEA)	Annual value of PM_{10} absorbed (£)			
	Corine 2006	LCM 2007	Difference (£)	Difference (%)
Woodland	£3.4 billion	£4.7 billion	-£1.2 billion	-36.25%
Enclosed farmland	£1.2 billion	£1.2 billion	£0.03 billion	2.17%
SNG	£0.18 billion	£0.19 billion	-£0.01 billion	-7.76%
OWWF	£0.09 billion	£0.05 billion	£0.04 billion	48.83%
MMH	£0.08 billion	£0.11 billion	-£0.03 billion	-32.00%
Coastal margin	£0.004 billion	£0.004 billion	£0.0001 billion	3.15%
Urban	£0	£0	£0	0%
Marine	£0	£0	£0	0%
TOTAL	£5.0 billion	£6.3 billion	-£1.2 billion	-24.19%
Habitat type (UK NEA)	**Annual value of SO_2 absorbed (£)**			
	Corine 2006	**LCM 2007**	**Difference (£)**	**Difference (%)**
Woodland	£3.5 million	£4.7 million	-£1.3 million	-35.99%
Enclosed farmland	£2.6 million	£2.4 million	£0.16 million	6.34%
SNG	£0.24 million	£0.35 million	-£0.11 million	-45.45%
OWWF	£0.12 million	£0.07 million	£0.06 million	45.09%
MMH	£0.14 million	£0.17 million	-£0.03 million	-22.53%
Coastal margin	£0.01 million	£0.01 million	£0.0003 million	5.14%
Urban	£0	£0	£0	0%
Marine	£0	£0	£0	0%
TOTAL	£6.5 million	£7.7 million	-£1.2 million	**-17.94%**

Source: AECOM

Table 18. Comparison of asset value of PM_{10} and SO_2 absorbed by natural capital in the UK using Corine 2006 and LCM 2007 data

Habitat type (UK NEA)	Asset value of PM_{10} absorbed (£)			
	Corine 2006	LCM 2007	Difference (£)	Difference (%)
Woodland	£88.2 billion	£120.1 billion	-£32.0 billion	-36.25%

Enclosed farmland	£31.5 billion	£30.8 billion	£0.68 billion	2.17%
SNG	£4.6 billion	£5.0 billion	-£0.36 billion	-7.76%
OWWF	£2.4 billion	£1.2 billion	£1.2 billion	48.83%
MMH	£2.1 billion	£2.7 billion	-£0.67 billion	-32.00%
Coastal margin	£0.11 billion	£0.10 billion	£0.003 billion	3.15%
Urban	£0	£0	£0	0%
Marine	£0	£0	£0	0%
TOTAL	£128.8 billion	£159.9 billion	-£31.1 billion	-24.19%

Habitat type (UK NEA)	Asset value of SO_2 absorbed (£)			
	Corine 2006	LCM 2007	Difference (£)	Difference (%)
Woodland	£88.8 million	£120.8 million	-£32.0 million	-35.99%
Enclosed farmland	£65.4 million	£61.2 million	£4.1 million	6.34%
SNG	£6.1 million	£8.9 million	-£2.8 million	-45.45%
OWWF	£3.1 million	£1.7 million	£1.4 million	45.08%
MMH	£3.6 million	£4.4 million	-£0.81 million	-22.53%
Coastal margin	£0.16 million	£0.15 million	£0.01 million	5.14%
Urban	£0	£0	£0	0%
Marine	£0	£0	£0	0%
TOTAL	£167.2 million	£197.2 million	-£30.0 million	**-17.94%**

Source: AECOM

Conclusions

This section provides a short overview of the findings for each of the research questions identified at the beginning of this report.

Question 1: How much PM_{10} and SO_2 was absorbed by the UK's natural capital in 2012 and what was the value of this service?

This research suggests that natural capital provides an important and valuable service in terms of its ability to absorb PM_{10} and SO_2 pollution. The level of dry deposition on the UK's natural capital in 2012 was estimated to be around 220,000 tonnes of PM_{10} and 2,800 tonnes of SO_2. Most deposition occurred on woodland habitats, both in absolute terms and in terms of the amount absorbed, relative to the total area of the habitat.

The total value of the PM_{10} absorbed was around £4.5 billion, while the value for SO_2 was £5.2 million. The asset value of the UK's natural capital, in terms of its ability to provide this service over the next 50 years, is estimated to be around £114.1 billion for PM_{10} and £134.0 million for SO_2. Note that the damage cost values used in this report are much higher than the damage costs used in the Powe and Willis paper. This is because Defra have produced more detailed estimates of air quality damage costs than were available when the Powe and Willis paper was written.

Rural areas accounted for around 80% of the value of PM_{10} absorption, although the average value of PM_{10} absorption in a rural grid square (£6,000) was much lower than in an urban (£13,000) or London grid square (£24,000) due to the higher population densities, and therefore higher damage costs, in urban areas. For SO_2, rural areas accounted for around 92% of the value and the average value in a rural grid square (£8) was higher than in an urban (£7) or London grid square (£3) since the damage cost estimates for SO_2 do not account for population density.

It is important to note that the estimated quantity of PM_{10} absorbed is higher than the Defra statistics on total annual emissions of PM_{10}, while that for SO_2 is lower. The reason that the estimates of PM_{10} absorption are higher than the estimated emissions appears to be due to the fact that the Defra emissions statistics do not fully account for natural or secondary sources of PM_{10}.

Question 2: How do the results compare to the i-Tree assessment 'Valuing London's Urban Forest'?

Estimates of the total amount of PM_{10} absorbed within the Corine 2012 model were higher than the i-Tree 2015 model as the latter only considered absorption by trees (rather than trees and grassland as in Corine). When focusing on the amount of PM_{10} absorbed by trees (rather than across all habitat types) the results were comparable across the Corine 2012 and i-Tree 2015 models, although the Corine 2012 estimates were somewhat lower. Estimates of the total amount of SO_2 absorbed in the Corine 2012 model were lower than the i-Tree 2015 model both when looking at all habitats and when focusing specifically on trees.

The results of the two models appear to be broadly comparable when focusing on PM_{10} absorption rates of tree based habitats (as in, woodlands). Estimates of PM_{10} absorption in the Corine 2012 model are likely to be lower than the i-Tree model due to the fact that its relatively coarse spatial scale can fail to identify small areas of woodland habitats within urban areas (see Question 4).

With regards to SO_2 absorption rates, the Corine 2012 model appears to underestimate SO_2 absorption relative to the i-Tree model, with the results being lower even when grassland and other habitats are included. This may be due to the fact that the model assumed wet deposition was equal to zero when in reality, wet deposition for SO_2 can be up to 1.5

times that of dry deposition, meaning that only about 40% of the SO_2 deposition is considered in this model.[31]

Further comparisons with other i-Tree assessments would be useful to provide a more complete assessment of the differences between the two approaches, together with a more detailed investigation into whether the differences are primarily land cover based (and therefore relate to accuracy of methods for determining tree cover) or are based on the processes and assumptions for pollution deposition and/or different pollution concentration data.

Question 3: How do the results compare to the i-Tree assessment 'Valuing London's Urban Forest'?

The level of dry deposition of PM_{10} was 21% lower in 2012, while that for SO_2 was 29% lower. This may be explained by a decrease in woodland cover, as well as differences in background pollution concentrations and the number of dry days. The higher number of on-leaf days in 2012 and the spatial configuration of habitat (for example, how much woodland is located in urban relative to rural habitats) may also have impacted the results. The value of PM_{10} absorbed was 11% lower in 2012, while that for SO_2 was 20% lower. This may be explained by differences in the area of land cover, spatial configuration of habitats, background pollution concentration, the proportion of dry and on-leaf days, and the willingness-to-pay for healthcare (and thereby deflation of the unit damage cost).

The difference in the value of the air quality regulation service observed across these two datasets is principally determined by two key factors: (1) differences in level of the background pollution; and (2) differences in the area of woodland habitats. The difference in background pollution concentrations is supported by Defra's data on air quality which suggests there has been an ongoing reduction in pollution emissions over this period. However, the difference in woodland cover recorded in the Corine datasets appears contrary to statistics provided by the Forestry Commission (FC) which suggest an increase in woodland habitat over this period.[32] This difference, when compared to FC statistics, is due to FC including felled and newly planted woodland, which the Corine dataset would not pick up. However, given that recently felled or newly-planted woodland is unlikely to have the pollution absorption capacity of fully established woodland, it is suggested that the Corine data provides a more useful approach for this modelling exercise.

Question 4: How do the estimates of PM_{10} and SO_2 absorption differ across the Corine and land cover map datasets?

There were significant differences in the area of different habitat types across the two datasets, with Corine 2006 recording around 34% less woodland cover than LCM 2007. The level of dry deposition of PM_{10} and SO_2 was around 18% lower in Corine 2006 based on differences in the area of land cover and the spatial configuration of habitats. The value of PM_{10} absorbed was around 24% lower in the Corine 2006 model while that for SO_2 was around 18% lower based on changes in the area of land cover and the spatial configuration of habitats.

The difference in habitat cover across the two datasets is likely to be due to a combination of differences in methodologies and classification systems used, and differences in the spatial resolution of the data. The higher levels of woodland cover and pollution absorption estimates in the LCM 2007 model are likely to be due, in part, to the fact that LCM data has a much finer spatial resolution and is therefore able to identify smaller areas of habitat. This is particularly important in urban areas where background pollution concentrations are higher and the value of pollution absorption is also higher due to the greater population density. In these situations, the LCM data is able to pick up small areas of tree cover which can be missed in the Corine data.

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[31] Pers. Comm. CEH, 2016

[32] Forestry Commission (2015), 'Forestry Statistics 2015', http://www.forestry.gov.uk/pdf/ForestryStatistics2015.pdf/$FILE/ForestryStatistics2015.pdf

Limitations and further research

The analysis in this report provides a broad indication of the potential value (in physical and monetary terms) of the role played by the UK's natural capital in absorbing pollution, which could be used to develop a range of decision support tools such as identifying optimal tree planting strategies for tackling air pollution. It is nevertheless recognised that the model used is relatively simplistic and can therefore only support a high level analysis.

In terms of physical flows, the results of this model are expected to underestimate the quantities of pollution absorbed by natural capital as only two pollutant types are included. In the i-Tree study, PM_{10} and SO_2 were found to make up only 13% and 3% of the total pollutant removal by trees, compared to O_3 (44%), NO_2 (32%), $PM_{2.5}$ (6.8%) and CO_2 (1.4%). Also, the estimated deposition rates for PM_{10} and SO_2 are lower than in other studies;[33,34] pollution deposition on freshwater and marine habitats is assumed to be zero when in reality there is likely to be some level of deposition to these habitats;[35,36] wet deposition is also assumed to be zero which may in reality be significant, particularly for SO_2; and, compared to the LCM data, Corine appears to underestimate tree cover in urban areas.

By contrast, the estimates of monetary flows may tend to overstate the benefits of pollution absorption in remote rural areas. This is because Defra's average damage cost figures are used, which do not fully account for population density within the surrounding area and may overestimate benefits in low density areas. Also, an average damage cost estimate is used based on emissions from transport sources. In reality, the main sources of pollution emissions are likely to vary and may have lower damage costs than transport emissions, particularly in remote areas with low transport emissions. Finally, the estimates of asset value may either understate or overstate the potential value of this service as they do not take into account future trends such as population growth and declining background pollution levels.

It is suggested that the robustness of the results could be further ground truthed and improved through the following refinements to the model:

- expanding the scope of the model to include additional pollutants such as O_3 and NO_2 by developing estimates of the average UK wide deposition rates for each additional pollutant; it is expected that this would increase the total estimated value of the service, although it would be important to take into account the fact that damage costs from additional pollution sources are not always cumulative
- undertaking sensitivity testing of the parameters used in the model, particularly in order to understand the implications of variation within deposition rates given uncertainty over the parameters used; this could be combined with further comparisons with air quality valuation studies based on the i-Tree model with a particular aim to see how the results compare in rural areas, and to establish if the differences in outputs are primarily land cover based or are based on the processes and assumptions used
- exploring the extent to which freshwater and marine habitats can absorb airborne pollutants
- investigating the extent to which wet deposition could be taken into account in the model

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[33] Erisman and Baldocchi (1994) 'Modelling dry deposition of SO2'.

[34] Zhang and others (2003) 'A revised parameterization for gaseous dry deposition in air-quality models'.

[35] Whelpdale and Shaw (1973) Sulphur dioxide removal by turbulent transfer over grass, snow, and water surfaces.

[36] Liu and others (2015) Dry deposition of particulate matter at an urban forest, wetland and lake surface in Beijing.

- undertaking a more accurate estimation of land cover and agreeing on an approach to measuring and classifying land cover types that can be replicated over time to develop more robust time series estimates

- expanding the spatial scope of the damage cost estimates to account for greater variation in population densities (e.g. small urban areas relative to large urban areas); the robustness of the estimates could be further enhanced if the Defra air quality damage costs were scalable by population density, as in, instead of having a single unit damage cost for different types of area (for example, rural vs. urban) a damage cost function was developed which estimated the total cost as a function of the local population density

- expanding the spatial scope of the damage cost estimates to account for greater variation in the sources of pollutant emissions; this approach could, for example, distinguish between agricultural relative to transport emissions and use appropriate damage cost estimates. This more detailed spatial scope could be used to identify pollution hotspots and where, for example, a vegetation corridor along a trunk road may hold significant value. In order to identify the potential significance of the impact on the results of this more detailed spatial assessment, a detailed local level analysis could be undertaken for a case study site and the results compared against the national level model to assess the difference in values estimates.

- accounting for future trends in the calculation of asset value. Developing a more sophisticated estimate of asset value would be relatively straightforward for the monetary flows side of the model e.g. through developing scenarios of changes in population density and income elasticity over time, however, developing scenarios for the physical flows side of the model, such as changes in background pollution concentrations, would be more complex as each change would have to be run through each of the grid squares within the model

To further improve the sophistication of the model and support more detailed analysis, experts from the Centre for Ecology and Hydrology (CEH) and the Joint Nature Conservation Committee (JNCC) have identified a number of additional areas of research:

- exploring the use of atmospheric dispersion models to account for some of the complex chemical interactions and transformation of pollutants

- reviewing whether there are additional benefits of pollution absorption which the damage cost estimates do not cover such as nitrogen deposition impacts on natural habitats

- exploring the extent to which the PM_{10} background concentrations include both primary and secondary fractions and the extent to which these are considered in the PM_{10} damage costs

- accounting for the potential for enhanced pollutant removal through occult deposition as a consequence of forest vegetation in upland areas

- developing a more sophisticated approach of estimating background pollution concentrations by considering the total accumulative flux to vegetation over the course of the year

- exploring the extent to which the surface area index leads to double counting as deposition velocities take into account canopy resistance

- revising the assumption that all vegetation can absorb the pollutants to the same degree and accounting for the fact that the ability of plants to do this may depend on the plant health, age and condition

- expanding the analysis of on-leaf and off-leaf days and dry or wet days to account for variance for agricultural habitats, drought periods, and lower stomatal uptake at night

Additional information

This section contains habitat classification tables and a table of data sources.

Habitat classification tables

Corine[37]		LCM[38]	UK NEA[39]	SEEA-EEA[40]	Powe and Willis[41]
111	Continuous urban fabric	Urban	Urban	Urban and associated developed areas	No vegetation
112	Discontinuous urban fabric	Suburban	Urban	Urban and associated developed areas	No vegetation
121	Industrial or commercial units	Urban	Urban	Urban and associated developed areas	No vegetation
122	Road and rail networks and associated land	Urban	Urban	Urban and associated developed areas	No vegetation
123	Port areas	Urban	Urban	Urban and associated developed areas	No vegetation
124	Airports	Urban	Urban	Urban and associated developed areas	No vegetation
131	Mineral extraction sites	Urban	Urban	Urban and associated developed areas	No vegetation
132	Dump sites	Urban	Urban	Urban and associated developed areas	No vegetation
133	Construction sites	Urban	Urban	Urban and associated developed areas	No vegetation
141	Green urban areas	Rough grassland	Semi-natural grassland	Semi-natural grassland	Heather or grass
142	Sport and leisure facilities	Rough grassland	Semi-natural grassland	Semi-natural grassland	Heather or grass
211	Non-irrigated arable	Arable and	Enclosed farmland	Rainfed and irrigated	Heather or

[37] Cole, B.; King, S.; Ogutu, B.; Palmer, D.; Smith, G.; Balzter, H. (2015). Corine land cover 2012 for the UK, Jersey and Guernsey. NERC Environmental Information Data Centre.

[38] CEH (2011), Land Cover Map 2007 Dataset documentation.

[39] UK National Ecosystem Assessment (2011) The UK National Ecosystem Assessment: Technical Report. UNEP-WCMC, Cambridge.

[40] ONS (2012), UK Natural Capital Land Cover in the UK.

[41] Powe and Willis (2004), 'Mortality and morbidity benefits of air pollution (SO2 and PM10) absorption attributable to woodland in Britain', Journal of Environmental Management, 70, 119-128.

Corine[37]		LCM[38]	UK NEA[39]	SEEA-EEA[40]	Powe and Willis[41]
	land	horticulture		herbaceous cropland	grass
212	Permanently irrigated land	Arable and horticulture	Enclosed farmland	Rainfed and irrigated herbaceous cropland	Heather or grass
213	Rice fields	Arable and horticulture	Enclosed farmland	Permanent crops, agriculture plantations	Heather or grass
221	Vineyards	Arable and horticulture	Enclosed farmland	Permanent crops, agriculture plantations	Heather or grass
222	Fruit trees and berry plantations	Arable and horticulture	Enclosed farmland	Permanent crops, agriculture plantations	Heather or grass
231	Pastures	Improved grassland	Enclosed farmland	Pastures/Improved grassland	Heather or grass
242	Complex cultivation patterns	Arable and horticulture	Enclosed farmland	Rainfed and irrigated herbaceous cropland	Heather or grass
243	Land principally occupied by agriculture, with significant areas of natural vegetation	Arable and horticulture	Enclosed farmland	Rainfed and irrigated herbaceous cropland	Heather or grass
311	Broad-leaved forest	Broadleaved woodland	Woodland	Broadleaved, mixed, and yew woodland	Deciduous
312	Coniferous forest	Coniferous woodland	Woodland	Coniferous woodland	Coniferous
313	Mixed forest	Broadleaved woodland	Woodland	Broadleaved, mixed, and yew woodland	Deciduous
321	Natural grasslands	Rough grassland, Neutral grassland, Acid grassland, Calcareous grassland	Semi-natural grassland	Semi-natural grassland	Heather or grass
322	Moors and heathland	Heather, Heather grassland, Montane habitat	Mountain, moorland, and heath	Shrubland, bushland, heathland	Heather or grass
324	Transitional woodland-shrub	Rough grassland	Semi-natural grassland	Semi-natural grassland	Heather or grass
331	Beaches, dunes, sands	Supra-littoral rock, Supra-littoral sediment	Coastal margin	Coastal margins	No vegetation
332	Bare rocks	Inland rock	Mountain, moorland, and heath	Barren land/Sparsely vegetated areas	No vegetation
333	Sparsely vegetated areas	Inland rock	Mountain, moorland, and heath	Barren land/Sparsely vegetated areas	No vegetation

Corine[37]	LCM[38]	UK NEA[39]	SEEA-EEA[40]	Powe and Willis[41]
334 Burnt areas	Inland rock	Mountain, moorland, and heath	Barren land/Sparsely vegetated areas	No vegetation
411 Inland marshes	Fen, marsh, and swamp	Openwater, freshwater, wetland, and floodplain	Open wetlands	Heather or grass
412 Peat bogs	Bog	Openwater, freshwater, wetland, and floodplain	Open wetlands	Heather or grass
421 Salt marshes	Saltmarsh	Coastal margin	Coastal margins	Heather or grass
422 Salines	Littoral sediment, Littoral rock	Marine	Territorial sea	No vegetation
423 Intertidal flats	Littoral sediment, Littoral rock	Marine	Territorial sea	No vegetation
511 Water courses	Freshwater	Openwater, freshwater, wetland, and floodplain	Inland water bodies	No vegetation
512 Water bodies	Freshwater	Openwater, freshwater, wetland, and floodplain	Inland water bodies	No vegetation
521 Coastal lagoons	Saltwater	Marine	Territorial sea	No vegetation
522 Estuaries	Saltwater	Marine	Territorial sea	No vegetation
523 Sea and ocean	Saltwater	Marine	Territorial sea	No vegetation

Data Sources

Dataset Name	Sourced from	Date Sourced	Description/How created	Copyright
MapPM102012g.csv (2012)	Defra data archive	13 January 2016	Background pollution maps at 1x1 km resolution. PM10/2012/Annual mean/Gravimetric units	Sourced from Defra webpages on 13/01/2016
MapSO212ann.csv (2012)	Defra data archive	13 January 2016	Background pollution maps at 1x1 km resolution. SO2/2012	Sourced from Defra webpages on 13/01/2016
mappm102006gh.csv (2006)	Defra data archive	2 February 2016	Gravimetric units – corrected to account for updated Partisol monitoring concentrations1	Sourced from Defra webpages on 02/02/2016

Dataset Name	Sourced from	Date Sourced	Description/How created	Copyright
mapso206ann.csv (2006)	Defra data archive	2 February 2016	Background pollution maps at 1x1 km resolution. SO2/2006	Sourced from Defra webpages on 02/02/2016
CLC12_UK (Corine)	CEH datasets	08 January 2016	Land cover data. See webpage for details (may have to apply changes dataset. Waiting for advice from CEH)	Reuse of this data must cite: Cole, B.; King, S.; Ogutu, B.; Palmer, D.; Smith, G.; Balzter, H. (2015). Corine land cover 2012 for the UK, Jersey and Guernsey. NERC Environmental Information Data Centre. This resource is made available under the terms of the Open Government Licence. Copyright rests with the European Commission. Acknowledgement: Produced by the University of Leicester, The Centre for Landscape and Climate Research and Specto Natura and supported by Defra and the European Environment Agency under Grant Agreement 3541/B2012/R0-GIO/EEA.55055 with funding by the European Union.
CHA12_UK (Corine)	CEH datasets	15 January 2016	This dataset for the UK, Jersey and Guernsey contains the Corine Land Cover (CLC) changes between 2006 and 2012. This shapefile has been created by combining the land cover change layers from the individual CLC database files for the UK, Jersey and Guernsey.	Reuse of this data must cite: Cole, B.; King, S.; Ogutu, B.; Palmer, D.; Smith, G.; Balzter, H. (2015). Corine land cover 2012 for the UK, Jersey and Guernsey. NERC Environmental Information Data Centre. This resource is made available under the terms of the Open Government Licence. Copyright rests with the European Commission. Acknowledgement: Produced by the University of Leicester, The Centre for Landscape and Climate Research and Specto Natura and supported by Defra and the European Environment Agency under Grant Agreement 3541/B2012/R0-GIO/EEA.55055 with funding by the European Union.
CLC06_UK (Corine)	CEH datasets	15 January	This dataset for the UK, Jersey and Guernsey contains the Corine Land Cover	Reuse of this data must cite: Cole, B.; King, S.; Ogutu, B.;

Dataset Name	Sourced from	Date Sourced	Description/How created	Copyright
		2016	(CLC) revised for 2006. This shapefile has been created from combining the 2006 land cover layers from the individual CLC database files for the UK, Jersey and Guernsey.	Palmer, D.; Smith, G.; Balzter, H. (2015). Corine land cover 2012 for the UK, Jersey and Guernsey. NERC Environmental Information Data Centre. This resource is made available under the terms of the Open Government Licence. Copyright rests with the European Commission. Acknowledgement: Produced by the University of Leicester, The Centre for Landscape and Climate Research and Specto Natura and supported by Defra and the European Environment Agency under Grant Agreement 3541/B2012/R0-GIO/EEA.55055 with funding by the European Union.
Land Cover Map 2007 (GB) and NI (Raster)	Direct from Defra via USB stick		LCM2007 is produced by the Centre for Ecology and Hydrology and is derived from a computer classification of satellite scenes obtained mainly from Landsat, IRS and SPOT sensors. It covers Great Britain and Northern Ireland and incorporates information derived from other ancillary datasets.	Morton, D., Rowland, C., Wood, C., Meek, L., Marston, C., Smith, G., Simpson, I.C. 2011. Final report for LCM2007 – the new UK land cover map. CS Technical Report No 11/07 NERC/Centre for Ecology & Hydrology 112pp. (CEH project number: C03259). Based upon LCM2007 © NERC (CEH) 2011. © Crown Copyright 2007, Ordnance Survey Licence number 100017572. © Third party licensors.
ONS Rural/urban classification 2011	ONS geoportal	18 January 2016	The 2011 rural-urban classification of output areas was released in August 2013. It is a revised version of the classification produced after the 2001 Census, but with additional detail in the urban domain. The product was sponsored by a cross-government working group comprising Department for Environment, Food and Rural Affairs, Department of the Communities and Local Government, Office for National Statistics and the Welsh government. Output areas are treated as 'urban' if they were allocated to a 2011 built-up area with a population of 10,000 or more. The urban domain is then further sub-divided into three broad morphological types based on the predominant settlement	Open Government Licence.

Dataset Name	Sourced from	Date Sourced	Description/How created	Copyright
			component. As with the previous version of the classification, the remaining 'rural' output areas are grouped into three broad morphological types based on the predominant settlement component. The classification also categorises output areas based on context – as in, whether the wider surrounding area of a given output area is sparsely populated or less sparsely populated.	
Northern Ireland Urban-Rural Classification (2005)	NISRA website	20 January 2016	Urban-Rural classification boundaries are available for Northern Ireland as defined by the Planning Service. These areas are defined from Settlement Development Limits (SDLs) which are a statistical classification and delineation of settlements. A review of the urban and rural classifications was undertaken and an initial report was published in 2015 which makes recommendations about new classifications, however unable to find a revised set of boundaries so going to use 2005 data.	Copyright not given. Sourced from NISRA (Northern Ireland equivalent to ONS)
Scotland 2013-2014 Urban rural classification	Scottish government website	20 January 2016	The Scottish government (SG) urban rural classification provides a consistent way of defining urban and rural areas across Scotland. The classification is based upon two main criteria: (i) population as defined by National Records of Scotland (NRS), and (ii) accessibility based on drive time analysis to differentiate between accessible and remote areas in Scotland. The classification is available in a two, three, six or eight fold form. The two-fold classification simply distinguishes between urban and rural areas through two categories, urban and rural, while the three-fold classification splits the rural category between accessible and remote. Most commonly used is the 6-fold classification which distinguishes between urban, rural, and remote areas through six categories. The 8-fold classification further distinguishes between remote and very remote regions. The classification is normally updated on a biennial basis, with the boundaries represented in this particular dataset reflective of the years 2013 to 2014	Copyright Scottish government, contains Ordnance Survey data © Crown copyright and database right (2016).