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Research paper on air filtration ecosystem services

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Contents

This research paper focuses on the role of terrestrial ecosystems in capturing and retaining pollutants and other substances and hence improving the quality of air, which in turn will have positive impact on people's health and also on the quality of built infrastructure and on the condition of ecosystems and biodiversity.

1. Description of the ecosystem service

Poor air quality is estimated to result in 4.5 million attributable deaths globally every year and is a major cause of morbidity. It also impacts negatively on visibility, infrastructure such as buildings, and on the state of habitats and species. By improving air quality, vegetation helps to mitigate these impacts on individuals' health and wellbeing as well as supporting habitat function and species survival.

Vegetation provides an air quality regulating service by capturing airborne pollutants and removing them from the atmosphere through: (a) the internal absorption of pollutants via stomatal uptake; and (b) the deposition of pollutants on external surfaces such as leaves and bark (Bignal et al., 2004, Smith et al., 1990). CICES (5.1) defines this as mediation of wastes or toxic substances of anthropogenic origin by micro-organisms, algae, plants and animals. For the purposes of this paper we are restricting the service to the mediation of air-borne pollutants.

1.1 Similar and related ecosystem services

The air filtration ecosystem service has close links with the measurement and valuation of other services which provide a health benefit, such as active outdoor recreation, noise abatement, local climate regulation and water purification. There will also be a link in terms of supporting or intermediate services to habitat and biodiversity related services, and as an intermediate service to terrestrial biomass provision.

This paper does not consider the use of the atmosphere as a sink for unmediated pollutant emissions, although there are parallels here with other flows of unmediated waste which are relevant to other services such water purification and carbon sequestration.

1.2 Definitional boundaries with respect to the ecosystem service

The starting point for consideration of the definitional boundary of this service is CICES 5.1:

"Mediation of wastes or toxic substances of anthropogenic origin … by micro-organisms, algae, plants, and animals … that mitigates their harmful effects and reduces the costs of disposal by other means. Examples of the service include dust filtration by urban trees."

This definition immediately raises two issues. First, to what extent is it meaningful or appropriate to limit the filtration service to pollutants of <u>anthropogenic</u> origin? It is clearly desirable to avoid multiple counting of the natural flux of emissions and re-absorption of volatile organic compounds from trees, for example. However, if such pollutants are blown in from another country, does it make sense for the absorption of the pollutants by local ecosystems not to be recorded as an ecosystem service (for the benefit of residents of that country)? And in any case, in practice it seems difficult if not impossible to distinguish between pollutants from natural sources and pollutants of anthropogenic origin. For both these reasons we conclude that the service should not be limited to just those pollutants of anthropogenic origin.

The second issue arising from the CICES definition is the limitation of the supply of the service to that delivered by micro-organisms, algae, plants, and animals. While bare soil and water are both components of natural ecosystems, and act as a surface for deposition of pollutants, it could be argued that the rate of pollution deposition to them is not biologically mediated, i.e. it does not differ if the soil is inert and lifeless, or is teeming with life yet still devoid of vegetation.[1] This would suggest that the contribution that ecosystems make to an improvement in air quality should be measured by reference to current levels compared with a counterfactual of 'no vegetation', which would imply that bare earth and water on their own cannot be seen as providing an air filtration ecosystem service.

Although further research is needed, in practice it seems likely that the average rates of dry deposition of pollutants to water and bare soil calculated from model outputs (Jones et al. 2017) are much lower than the rates for all vegetation types, including the generally lower values revealed for absorption by crops, for O_3 and NO_2 in particular (although they can be similar to the rates for crops in the case of PM_{10} and $PM_{2.5}$). For the purpose of scenario comparison in model-based assessments, the use of bare soil can be seen as the most appropriate counterfactual when assessing the benefits of existing vegetation. One caveat to consider, however, is that when using bare soil as a counterfactual, an increased contribution of wind-blown dust (crustal material) to modelled concentrations of $PM_{2.5}$ and PM_{10} needs to be accounted for. Trees in certain locations may also reduce air quality by trapping pollution rather than absorbing it. As ecosystem services can have both benefits and unintended (negative) consequences, any accounting framework needs to accommodate both positive and negative effects in a consistent way to accurately reflect the net contribution of the ecosystem service to improving air quality.

For the purposes of estimating the service provided by trees, the counterfactual often adopted is to model the effect of trees versus a baseline condition without trees (i.e. with the baseline condition of base water, soil and herbaceous vegetation in the area). This approach would avoid double counting the service provided by other forms of vegetation.

Our conclusion is that open freshwaters, as they are part of the range of ecosystems in any area, can and probably should be included in order to be consistent with counterfactuals assumed for other services, but that in practice unless they cover a large area they are unlikely to absorb large quantities of air pollutants.

2. Measuring the ecosystem service

The reduction in pollutant concentrations or exposure to pollution at any location due to vegetation is an outcome of all the interactions between vegetation types, meteorology and the concentration and chemistry of pollutants that have occurred in the parcel of air before reaching that location (Jones et al. 2017). The location and timing of these interactions may be different due to differences in the location and timing of the reductions in concentrations and exposure.

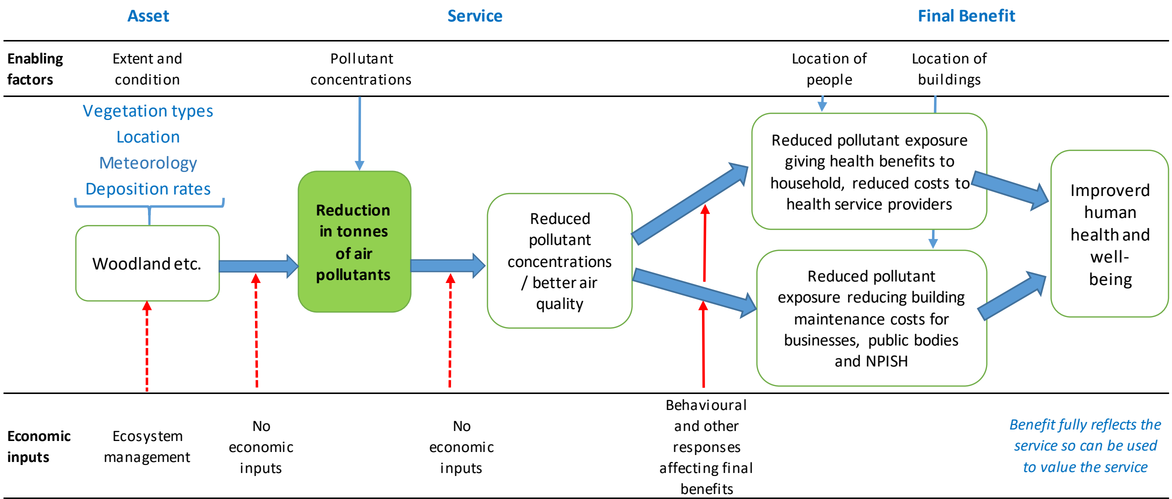
2.1 Distinguishing between the ecosystem service and the benefit

While the capture of pollutants is likely to be seen as the most relevant physical metric for the service, it is important to recognise that the service can only be seen as taking place when it provides a benefit in terms of reduced exposure. Note also that the absolute volume of pollutants captured is not a good measure of the value of the service, because the capture of the smallest particles (e.g. $PM_{2.5}$) provides most benefit in terms of the impact on human health

[1] A possible exception here is the removal of carbon monoxide by biological agents in the soil.

The following logic chain is our attempt to set out where some of these factors feature in determining the flow of services.

Figure 1: Logic chain for air filtration services



Note Different physical metrics for each different pollutant, which will give a different range of benefits

In Figure 1, the removal of air pollutants by ecosystems is seen as reducing concentrations of air pollutants and improving air quality. Depending upon the location of people and buildings, this improved air quality contributes to the provision of a range of final benefits.

The two categories of final benefit shown in Figure 1 are not necessarily exhaustive. There are impacts on other, more sensitive ecosystems and the services they provide (e.g. agricultural and horticultural crops), as well as further 'downstream' benefits. Some of these other benefits are discussed in the section on valuation below.

2.2 Metrics for measuring the ecosystem service

Metrics for physical ecosystem service flows include both the quantity of pollution removed, but also the change in pollution concentration. While the latter can be used as a proxy for exposure, it is primarily a metric of the physical service flow. The final benefit that results from the service is a reduction in air-pollution related impacts, e.g. improved human health and reduced damage to buildings.

The choice of unit will depend upon the view taken on the nature of the service. The physical process involves the capture of pollutants by vegetation and will be measured in tonnes: different pollutants have different deposition rates and different impacts and will need to be distinguished. In the studies to date, most attention has been paid to measuring the contribution of ecosystems to capturing particulate matter ($PM_{2.5}$ and PM_{10}). Analyses of the impact of pollutant capture on $PM_{2.5}$ and PM_{10} are often combined because there is significant correlation between the two measures.

Other pollutants that have been modelled include ammonia (NH_3), ozone (O_3), nitrogen dioxide (NO_2), sulphur dioxide (SO_2) and carbon monoxide (CO), although not all of these have been valued in monetary terms. This is not a comprehensive list of pollutants that could be modelled. Because the health impacts of particulate matter are so much greater than other air pollutants, an aggregate measure of the tonnes of pollutant captured would not be a meaningful indicator of the service provided.

Another physical metric is the change in pollution concentration, measured as change in µg m^{-3} concentration of the pollutant. In terms of final benefits, yet another metric could be the change in human health due to the change in concentrations.

2.3 Key users and beneficiaries

The benefit is largely defined by the number and location of the users/beneficiaries in relation to the service provided. While a metric of exposure can be calculated as a change in population-weighted concentration, i.e. giving a greater weighting to the concentration changes occurring in areas with the greatest population, this is probably most accurately considered as a proxy. The health benefit can be calculated as the estimated reduction in health impacts arising from that change in concentration. For vegetation in urban centres, this should consider the temporal aspects of population mobility, bringing larger numbers of receptors into more highly polluted areas during working days (Reis et al., 2018). While this does not affect population level exposure assessments at the national scale, for local scale and individual/small population group exposure, the differences in the impact of pollutant removal by vegetation in urban centres could be substantial.

Although the ultimate beneficiaries in terms of reduced health impacts may include health service providers, the service is viewed as being a transaction between the ecosystem and households, who are therefore seen as the users in the supply-use tables.

For reductions in the impact of air pollution on buildings, the users (and the beneficiaries) are likely to be the owners of the buildings. In many countries the impact of air pollutants on buildings has reduced significantly in recent years, however it may still be a relevant consideration for some countries with historic sites in exposed locations.

3. Summary of common data sources and models for physical flow estimates

The basic premise to modelling pollution removal by vegetation is that the flux in pollutants equals deposition velocity to vegetation times the local pollution concentration. Modelling these effects thus requires information about the local vegetation resource (e.g. leaf area, percent deciduous, leaf on/off dates), local meteorology (e.g. air temperature, wind speed, solar radiation, humidity) and local pollution concentrations to estimate pollution removal by vegetation (Nowak et al. 2013, 2014). These data are combined with atmospheric height information to estimate changes in pollution concentration due to pollution removal. This process can be calculated on an hourly basis in free i-Tree software[2] that can be used globally. The sources for these data are local monitoring data (weather, pollution, atmospheric soundings, which are preloaded in the i-Tree Eco model) and local tree data provided by the model user.

To address larger, more regional issues of pollutant transport and pollutant formation, larger scale models are needed that require more regional land cover, pollutant emission and meteorological data. For example, photochemical models, such as Comprehensive Air Quality Model with Extensions (CAMx) (US EPA 2018) can be used to estimate ozone concentrations. The degree to which vegetation effects are incorporated within these regional models varies.

In principle absorption of different pollutants could be estimated using different models. For NO_2, for example, local emissions and concentrations are strongly correlated, while for $PM_{2.5}$ and ozone, the long range transport element is substantially larger and may even dominate, in which case reliance on estimates of concentrations based on local emissions could give misleading results.

[2] www.itreetools.org

As the service is not 'used' if there are no beneficiaries, the location of those receiving health benefits is also an important determinant of the amount and value of air filtration service provided (Jones et al. 2017). Generally this information will be taken from the Census of Population but as noted above, information about the location of those entering cities to work, and potentially on the location and ownership of buildings benefitting from reduced exposure to air pollutants, will also be important. It is worth noting that the health benefits resulting from pollutant removal can be experienced in a different location to where the removal happens. For example, a large forested area upwind of a city will provide substantial pollutant removal, especially of particulate matter, thereby lowering the background levels of pollution that people in that city are exposed to.

4. Measuring future flows of ecosystem services

This section considers the extent to which future changes in the delivery of the service are dependent upon future ecosystem extent and condition, and the influence of other factors such as climate change, future population levels and changes in location, and future pollutant emission levels.

Modelling of pollution removal by vegetation is dependent upon vegetation type, meteorological conditions and pollution concentrations; data on the location of human populations and buildings is also needed in order to value the ecosystem service. Modelling of changes in the volume and value of future pollution removal will ideally need information on the projected changes in the each of these variables. Some of these data can potentially be obtained from climate change projections (e.g. NARCCAP 2018), demographic projections (e.g. US Census Bureau 2018) and estimated changes in land cover (e.g. Nowak and Greenfield 2018).

For rates of pollution removal, the biggest driver is expected to be changes in pollution concentrations, since the rate of removal is highly dependent on concentrations. Future concentrations will be affected by future emission levels, driven inter alia by technological and legal changes such as use of electric cars and environmental emission regulations. For $PM_{2.5}$, the amount of woodland is also important, but changes in woodland would need to occur over a large area before they substantially reduce pollution concentrations at anything other than a local scale.

Overall, however, the level of service is governed by the number of beneficiaries, and their location in relation to where pollution concentrations are highest. The key point here is that estimated changes in the asset value of the service are likely to depend more upon changes in external factors than on changes in the condition of the natural asset itself.

5. Valuation of the ecosystem service

The removal of air pollutants by ecosystems constitutes an ecosystem service, resulting in the intermediate benefit of improved air quality. When combined with other inputs across a range of production functions, improved air quality contributes to the production of a number of final benefits all of which, in principle, can be valued in economic terms. The focus here is on valuing the ecosystem's contribution to those final benefits. Thus, in many instances, improved air quality is perhaps best understood as an input into the production and consumption of other, final benefits which can be directly valued. For example, cleaner air is one of many inputs to the production of improvements in health states. Air quality improvements – partly arising as a result of air filtration services provided by ecosystems – can thus be valued in terms of: (i) improved health outcomes; and (ii) avoided resource costs (such as fewer healthcare costs) due to the reduced incidence of, for example, respiratory illness.

Figure 1 above illustrates the logic and intuition behind valuing air filtration services. The ecosystem service generates an intermediate benefit – in this case, improved air quality – which generates value via a number of impact pathways. The challenge then is to identify that share of the value which can be attributed to air quality improvements produced by the ecosystem service.

As noted earlier, the two categories of final benefit in Figure 1 are not exhaustive. Impacts on agricultural productivity are a long standing focus of studies of the economic impacts of air quality, although the direction of effect depends on background concentrations of particular air pollutants (see, for example, Long et al. 2005 and Lobell and Gourdji 2012). In addition, some of these categories could be further disaggregated as these final benefits may in fact contribute to a cascade of indirect or second-order effects that could in principle be valued. For instance, Mohai et al. (2011) linked poor air quality in schools to poorer student health and academic performance, raising questions about whether the impact of air quality on human capital formation should be included in valuing air filtration services. Ebenstein et al. (2016), using richly detailed data for Israel, show that acute instances of high concentrations of particulate matter lead to lower scores in high-stakes school examinations, which in turn has far-reaching consequences for earnings trajectories years later[3].

Notwithstanding these additional considerations about the extent and nature of final benefits, once the impact pathways and final benefits to be included have been identified, the sizable challenge of isolating the share of the value that can be attributed to air filtration services remains. Some of these values might plausibly be dealt with through the valuation of other services (e.g. recreational services), albeit linking this explicitly to air filtration services requires some quantification of the way in which cleaner air leads to greater utilisation of outdoor recreational opportunities.

As a starting point for thinking about this valuation for national accounting purposes – taking a cue from a well-established categorisation in environmental economics – Atkinson and Obst (2017) distinguish three channels in which ecosystem services ultimately provide benefits to people and businesses. These are: (a) as inputs to economic production; (b) as joint inputs to household final consumption; and (c) inputs which directly contribute to household wellbeing (that is, there is no existing economic production or household consumption where these services are inputs, and the services are consumed directly in generating benefits without any other (produced) inputs).

In principle all of these channels are useful for understanding the contribution of air filtration services in providing benefits to people. In some cases the precise channel will depend on the nature of the beneficiary, as in the case of reduced soiling to buildings which might be either commercial (Channel (a) or residential properties (Channels (b) or (c)).

Whatever the case, a likely institutional arrangement is approximated by the cost savings that are enjoyed as a result of better air quality. Put another way, in the absence of air filtration services, fewer resources need to be used to maintain buildings than would otherwise be the case. In this sense, this maintenance is the cost of replacing (or a substitute for) the service, subject to the normal caveats as to whether society would choose to replace the service were it to be removed. At the very least there is a decision to make as to whether to incur this expenditure or not.

The transactional character of health benefits can be understood in a similar way (at least in part). The absence of air filtration services involves resource costs, which otherwise are incurred when people are ill as a result of worsening air quality. Institutional units (e.g. the health-care sector) have an interest in maintaining the health of those served by these public or private organisations. In this

[3] Other intriguing pathways from air quality to socioeconomic outcome continue to be identified. Bondy et al. (2018) find a causal explanation for concentrations of PM2.5 in London and the incidence of violent crime. While this causal relationship appears robust in this example, the exact mechanism underpinning the result is far less obvious. Herrnstadt and Muehlegger (2015) find similar results in Chicago.

sense, health treatment for a respiratory illness is a replacement for the ecosystem service which maintains health by reducing the risk of becoming ill in the first place. The resources that otherwise would be used are associated with tangible costs: e.g. outlays on consultations, treatments and so on. That said, institutions for health-care will differ across countries, necessitating an inspection of specific arrangements. There may be differences within countries too – private and public provision – although there might be a common basis for ascertaining the (saved) costs of illness. Of course, resource use is not confined to producers such as health-care bodies alone (see, for example, Drummond *et al*. 1991). Households will also use economic resources which translate into costs savings.

The most important (in terms of value) and most researched impact pathways for valuing air filtration services relate the effect of changing air quality on human health. Several variants of 'health-based' approaches are used. These include cost-based approaches, where air filtration services reduce costs by implicitly replacing health care resources that would otherwise have been required to treat respiratory illness. One challenge with cost-based approaches is that they could yield wildly different values for exactly the same health outcome simply because of differences in health care provision (e.g. expensive private versus inexpensive public care). Alternatively, several approaches attempt to value the benefits of better health directly, rather than focusing on cost savings.

In what follows, we explore a range of issues and challenges related to this valuation context.

5.1 Health valuation

A focus on health outcomes might proceed by exploring a number of physical end-points. These end-points include risks associated with premature mortality as well as morbidity. The latter, in turn, might refer to a variety of acute and chronic conditions as well as pollution-related health events (such as hospital admissions or emergency department visits). In effect, these are the "quantities" to which appropriate values or unit costs could be assigned. In the case of premature mortality, there are further options as to how to describe this end-point.

Notably there is the concept of a "statistical life": the premature fatalities that are reckoned to result from some estimated risk arising, for example, from a unit change in ambient air quality (measured in terms of the prevalence of some air pollutant). The product of this physical metric and estimates of the value of statistical life (VSL) are typically used in policy evaluations as a means of assessing the economic value of changes in mortality risks.

This VSL is the value that people place on small changes in mortality risks. There is a variety of ways in which VSL might be estimated. Broadly speaking, these might be distinguished as to whether the underlying valuation concept is willingness to pay to secure a risk reduction, or the willingness to accept compensation for tolerating higher than "normal" risks. The latter have involved hedonic wage risk studies. Studies of the former have typically involved use of stated preference techniques, but it also might involve looking at revealed behaviour such as avertive expenditures.

The advantage of approaches based on revealed behaviour is that they reflect the implicit value of changes in health risks based on actual transactions, albeit in somewhat different institutional contexts. But there are two important limitations. First, if we are interested in ex-ante valuations of changes in air quality that have yet to be experienced, the legitimacy of using revealed behavioural responses to historical air quality may be reduced. Second, it is not clear that peoples' observed behaviour is a reliable medium through which to extract values for goods and services that are unfamiliar or poorly understood. In principle, individuals would need to understand and consider ambient air quality, their exposure rate, and the impact on their health in order to hold stable preferences which could be revealed in their behaviour.

But while stated preference approaches represent people being asked about hypothetical transactions involving changes in health risks, this is an attempt to mimic an institutional context where the benefit can be purchased. It also has the advantage of more ready and consistent distillation of the empirical record as meta-studies such as OECD (2012) and applications of such findings by World Bank (2016) arguably demonstrate.

Estimates of the VSL are typically applied as a "standard value": that is, an estimate that is invariant across risks (and their levels[4]) as well as across different groups whose mortality risks are affected. One prominent venue in which this debate plays out is the way in which the age of individuals may (or may not) matter. In the air pollution example, the risk may well be immediate for older people since it is known that older people tend to be most affected by air pollution. But for younger people, while immediate benefits are considerably less, the benefits of reducing pollution may over time be greater. Also younger children may be more sensitive than older children to changes in pollution.

The question naturally arises as to whether older people (e.g. 70 years old) place the same value to avoid a mortality risk as someone younger (e.g. 35 years old). More critically, air filtration services may save a disproportionate number of lives in the "very old" category, by reducing mortality risks and extending the (statistical) life by days, weeks or even months. The issue, then, is what weight should be attached to such risk reductions in an economic assessment.

A practical response to this issue is the notion of the "value of a statistical life year" (or VSLY). In essence, VSLY assumes a straight-line decline in value with age, given that there are fewer years of healthy life expectancy remaining. What this means is that issues such as the scarcity value of time itself (i.e. fewer years left results in a higher value for the remaining years) are omitted. Put another way, what the VSLY approach does is to replace the assumption (in standard applications of VSL) that age does not matter with an alternative assumption that age not only matters but it matters in a particular way (i.e. as specified by the assumed VSLY conversion calculation such as a constant value (that is typically also discounted).

5.2 Quality-adjusted life years

An alternative physical metric to describe health end-points, which might then be subsequently valued, is the notion of a quality-adjusted life year or QALY. This metric evaluates the degree of change in health arising from a specific condition. As a result, the focus is on quality of life, rather than quantity (whether summarised as a statistical life or statistical life-year).

Specifically, the method utilises survey findings where respondents are required to make evaluative judgements about the way in which their quality of life might change as a result of a variety of permutations of changes in their health state. For example, the particular approach used in the UK for health evaluation (e.g. Weinstein, 2015) is based on five health dimensions (mobility, self-care, usual activities, pain and discomfort, anxiety and depression) described at three levels of severity (no problems, some problems and severe problems).[5] In turn, utility scales are inferred from these choices which are typically bounded between 1 (perfect health) and 0 (death).

[4] For example, small differences in the initial (baseline) risk level are usually assumed to have little effect in VSL studies.

[5] This is the EuroQoL approach.

For example, and linking this QALY concept to air filtration services, suppose the effect of air filtration services is to add 1 year of life expectancy to people's health status. If this additional year was to be enjoyed in otherwise perfect health then this benefit would equate to 1 QALY. However, if quality of life is 0.5 – perhaps because of some underlying health condition – then this life extension would equate to 0.5 QALYs (that is, 1 additional year weighted or adjusted by its apparent quality).

An advantage to this approach is that it allows mortality and morbidity risks to be considered together. In turn, these QALYs could be used as the physical basis for valuation utilising monetary resource costs (per QALY) or values based on broader notions of wellbeing (e.g. willingness to pay approaches). Disadvantages include the incompleteness of the underlying data on which QALYs are based as well as assumptions (rather than evidence) about preferences embedded in the formulation of the resulting utility scales, and the difficulty of updating the estimates. As a practical matter, QALYs are a central element of the institutional context for public decisions on health policy in some countries (notably, the UK) but by no means all (notably, the US) (see, for example, Weinstein, 2015).

5.3 Costs of illness

One approach might focus, and perhaps build, on those values which already leave a trace in actual transactions. The 'costs of illness' (COI) is a long-standing approach in the health literature in terms of guiding thinking about the burdens of specific conditions on healthcare institutions (and households). This refers to a range of costs, which can viewed from a number of perspectives. For example, one starting point might distinguish between direct and indirect costs.[6] However, there is a risk is that this terminology – while reasonably common in the COI literature – leads to confusions with terms used to characterise expenditures from a national accounting standpoint.

In the light of this, a reasonable starting point is perhaps that of Drummond et al. (1991). This paper looks at the economic resources (broadly construed) used by different institutional units as a result of changes in health states, where these units are the health-care sector, households (e.g. patients and their families), and other economic sectors. From this standpoint, air filtration services represent "resources savings" in the sense of releasing those actors in these institutional units from (otherwise) incurring costs to maintain and restore health states.

The nature of these resource savings is important. Many of them refer to actual expenditures which, as a result of the air filtration service, do not need to be made. These expenditures include costs associated with medical care and treatment as well as rehabilitation or management of a condition. For households, expenditures may involve the purchase of over the counter medication, but it might also involve less obvious expenditures such as financial outlays which are part of the travel costs (e.g. to and from medical facilities for patients and their families). Household time costs will be a significant resource saving when health states change both in this travel cost example as well as more broadly (e.g. volunteer time provided as a result of having to care for family members who are ill). This cost, in turn, might entail a mixture of lost productivity and the costs of lost leisure (e.g. where the latter might reflect the fact of a reallocation of leisure time, owing to family members having to care for those who are ill). This is possibly an extensive range of cost savings, but characterised in this way the process of deciding which components are consistent with different accounting practices arguably becomes a little more straightforward.

[6] See, for example, for a succinct definition: Cost of Illness [online]. (2016). York; York Health Economics Consortium; 2016. https://www.yhec.co.uk/glossary/cost-of-illness/

The above costs all refer to changes in resource use arising as a result of changes in health states. In the case of air filtration services, this will be specific health conditions (e.g. mortality or morbidity risk endpoints) which change when air quality changes. In other words, specific disease (condition) risks are the focus here, and so costs need to refer to the unit costs that are saved as a result of air filtration services.[7] The definition of "cost", for expenditures related to the healthcare sector, may have different interpretations. These different interpretations will have different levels of precision. Important decisions also involve how to apportion shared overheads to specific conditions (Drummond *et al*. 1991). Moreover, a narrow definition would look only at the sum of all diagnosis-specific medical costs, whereas a broader definition might involve estimating those additional costs for people diagnosed with a specific condition which might be confidently considered to be "co-morbidities" (a different ailment but related to another, perhaps underlying, condition).

Relatively fine grained, but data intensive, approaches might look at actual costs for a hospital of treating a given condition[8]. Use of average hospital costs might be a more general, but less fine-tuned, approach. Alternatively it might be possible to use reference costs in the sense of regulated rates of reimbursement for healthcare facilities such as hospitals. There are official prices and payment rules for particular healthcare interventions (e.g. consultations) and treatments - these are the tariffs paid by a health authorities (such as the National Health Service in the UK or Medicare in the US). These have the virtue of representing the transaction between a buyer and seller, albeit one which might not reflect the actual costs of the intervention or treatment in some cases.

5.4 Averting behaviour

Households (and individuals) can take actions which protect against their chances of experiencing negative impacts as a result of adverse ambient air quality. In fact, some of those items counted as burdens of specific conditions of ill-health in the 'costs of illness' approaches described above, are an illustration of these actions. Generally speaking, examples of averting behaviour entail an array of financial outlays and/or time costs. In turn, some of the economic value arising from averting behaviour may be consistent with the exchange values, and some may not, depending on the conventions adopted.

An archetypal example is parents or guardians keeping children indoors when ambient air quality is relatively poor. In this case, the averting behaviour may involve money costs by having to pay for child-care and so on. However, it could also involve time costs of a parent having to allocate time to looking after their now house-bound children. In some instances, this cost is reallocated leisure time. In other cases, this cost might involve taking time off work and be associated with a loss of productivity and perhaps foregone wages or salaries.

The costs of avertive behaviour are a component of the economic burden of air pollution. By implication, these are cost savings – and so-called benefits – when air quality is better than in some reference point situation. Air filtration services from ecosystems, other things being equal, improve air quality in a given location. For those households who live or otherwise experience good air quality, this cleaner air may obviate the need for (some) costly averting behaviour and so, in

[7] This is a prevalence based perspective, assessing the burden of illness, for a specific condition (e.g. chronic obstructive pulmonary disease or COPD), over the course of a given period (e.g. a year). An alternative is an incidence based approach which, by contrast, focuses on the lifetime profile of burdens for a given group of people diagnosed as having a specific condition. In this sense, the latter is a stock-like metric perhaps interpretable as the cost liability arising in the population of those individuals diagnosed as having a specific condition. The former is a flow of the current costs arising in any particular period.

[8] See for example Tsiachristas et al. (2017) in a study of the costs of self-harm in the UK.

principle, when we speak of the value of this particular ecosystem service, then this 'cost saving' is one component.

One question is whether the dose component of empirical dose-response functions (upon which damage cost or impact pathway approaches are typically based) accurately reflects the role of averting behaviour. Put another way, some of the population will be exposed to changes in air quality resulting from air filtration services, and some will not (possibly as a result of induced changes in behaviour). So the issue is whether any estimated relationship between changes in air quality and changes in health states is an accurate reflection of what happened in any accounting period. Even where dose-response relationships result in broadly defensible physical end-points, there is likely to be an issue about the price to attach to air filtration services. That is, the cost savings arising from relieving the need for averting behaviour will, in all likelihood, not be reflected in the health values attached to physical end-points (whether these are based on costs-of-illness, human capital or some non-market valuation approach).

As a practical matter, it is not straightforward to gather data on averting behaviour and a number of further empirical complications arise too. There may be a good reason why such studies are the exception rather than the rule and this will have a bearing on whether the approach can be routinely applied in the accounting context.

5.5 Damage cost approaches versus valuing the benefits of improved air quality

At least some of the literature (and perhaps reflected in Table 6.1 in the Technical Recommendations) suggests that there are two broad approaches to valuing air quality:

i. Focussing on the damage costs induced by pollutants, and
ii. Valuing the benefits of reductions in pollutant concentrations.

In general, these are opposite sides of the same coin: for any given level of pollution, the value of damages from the marginal unit of pollution is the same as the value of benefits of avoiding it.[9] Having said that, although the valuation of benefits versus damage costs should be equivalent at the margin, in practice there may be significant differences. These could arise because of:

- Differences in conceptual foundations and whether valuation focus is on direct effects only, or whether is it relevant to trace and include the indirect effects of air quality improvements as well (WHO 2013);
- Whether the focus is on different components of the ecosystem service;[10]
- The use of different valuation methods, whether based on observed willingness to pay (Bateman et al. 2001), stated willingness to pay (Welsch 2006), observed health impacts (Gao 2015), or life satisfaction (Levinson 2012);[11]
- Different data availability, context and scales of analysis, such that even when comparing two studies using the same assumptions across all the criteria listed above, different

[9] There may be some exceptions to this rule. In particular, if there are threshold effects such as restrictions on activities when pollution exceeds a specific level.
[10] Variously, studies may attempt to value changes of specific pollutants on health, groups of pollutants on health, specific or groups of pollutants on recreation, impacts on life satisfaction, effects on labour productivity, or any combination of these.
[11] Even within these categories, further differences arise when for example health impacts are valued in terms of treatment costs, life satisfaction, value of statistical life, etc. WHO (2013), for instance, examined the impacts of both long- and short-term exposure to $PM_{2.5}$, PM_{10}, O_3, NO_2 on all-cause mortality, cause-specific mortality, post-neonatal mortality, prevalence of bronchitis in children, and the incidence of chronic bronchitis in adults.

locations, initial levels of pollution, ecosystem extents, types of data available, and scales of analysis (street level to international) will mean that a wide range of values for air quality improvements is possible.

In practice, providing values for air quality improvements entails significant simplification. Pragmatically, many governments adopt a damage cost approach, in which centrally agreed values are applied nationally. Typically this approach attempts to estimate a marginal value for removing the marginal tonne of pollutant. This marginal value is then multiplied by the mass of pollutant absorbed by the ecosystem (e.g. urban trees).

This approach raises several issues:

i. How do we come up with that marginal value in the first place?
ii. Marginal values depend on baseline pollution levels and are unlikely to be appropriate for valuing non-marginal changes
iii. The context in which the marginal value is derived (e.g. central parts of cities) may prevent use in other contexts (e.g. rural areas)
iv. If health impacts are included, then the marginal value needs to be adjusted for exposure rates (e.g. population density). This population density approach is used in the US Forest Service's i-Tree Eco model for valuing $PM_{2.5}$, O_3, SO_2 and NO_2. Generally, using a constant marginal value will entail excessive approximation and adapting these data even at the national level, perhaps by weighting by population density, would seem to provide a significant improvement.

5.6 Hedonic studies

It is plausible to imagine that hedonic studies of air quality and residential property prices provide another means to help understand the way in which households value air filtration services as an input to household consumption (Smith and Huang 1995). This is a long-standing means of using an actual transaction for a tangible good which reveals, in turn, the value of a transaction in an otherwise intangible service. In this sense, the institutional arrangement for transacting air filtration services is already in place: it is mediated, as one of a great many dimensions, through the housing market.

Assuming this value can be identified, however, determining its actual effect might be a challenge. That is, the premium that a property commands (other things being equal) in an area of higher air quality, because of proximity to vegetation providing air filtration services, will itself be a value based on the provision of a bundle of benefits, such as those in the final column of Figure 1. Whether it is possible to further tease out these benefit constituents is another matter. The extent to which this itself matters is also open to question. There is a parallel here to any transaction where the buyer's precise motives are a latent dimension of the exchange. In theory the important thing is the transaction between buyer and seller reflects the exchange of something identifiable, in this case (differences in) air quality arising from air filtration services and mediated through the purchase in the property market.

If such studies can be translated into value end-points per unit of air pollutant (e.g. $PM_{2.5}$) then this could be linked to studies which estimate the contribution of vegetation and so on to air quality in specific areas. These values would reflect a range of possible benefits rather than human health per se, and it is unlikely to be straightforward or even possible to disentangle the values into further constituent parts at least in a direct manner.

Quantification of these health impacts would require the following sets of information:

1. Estimates of pollution exposure based either on locally measured data on concentrations and/or on dispersion modelling, linked to the location of areas of population, which provides population-weighted concentration levels.
2. Response functions relating this exposure to death and illness derived from epidemiological studies such as those carried out in the UK, Europe, the USA and other locations.
3. Information on the underlying incidence or prevalence of illness and death, derived from national statistics on death and hospital admissions.
4. Unit values describing the monetary equivalent of health impacts. These may include three elements describing lost productivity, healthcare costs avoided, and lost utility (relating to the value that we place on living a healthy and long life).

5.7 Selection of response functions

There exist alternative recommendations for the functions to be used for quantification of impacts:

- WHO (2013): HRAPIE study (Health Response to Air Pollutants in Europe), which was adopted for analysis by the European Commission in the revision of its Thematic Strategy on Air Pollution.
- US EPA (2011): For analysis of various measures for air quality improvement.
- Global Burden of Disease (GBD) for assessment of the global burden of disease[12].

The World Health Organsation (WHO) and the United States Environmental Protection Agency (US EPA) both recommend quantification of a significant number of additional morbidity effects, including chronic bronchitis, exacerbation of respiratory conditions and 'restricted activity days' including lost work days.

6. Case studies

i-Tree. Economic valuation of pollution removal in i-Tree has adopted both approaches: 1) externality values and 2) health values. Externality values are the estimated cost of pollution to society (e.g. damage to humans, vegetation, ecosystems, visibility) that is not accounted for in the market price of the goods or services that produced the pollution. These values are estimated through economic valuation procedures (e.g. Van Essen et al. 2011), based on estimated impacts per tonne of pollution which are then multiplied by tonnes of pollution removal to obtain an estimated value.

In contrast, health values focus on the value of improved health (e.g. reduced mortality, respiratory symptoms, hospital admissions) due to pollution removal. These values are based on pollution removal and consequent changes in pollution concentration and human health impacts, but also human population characteristics such as population density and age demographics. Thus, values per tonne of pollution removed can vary substantially as human populations change across a landscape.

These data are then combined with local demographic information to estimate health impacts and values using procedures from the US EPA BenMAP model (US EPA, 2012; Nowak at al. 2013, 2014). The results are based on local pollutant concentration changes, but these changes will also impact on pollution concentrations and formation (e.g. ozone) in areas downwind of the removal (e.g. Nowak et al. 2000).

[12] http://www.healthdata.org/gbd

The Netherlands. An initial pilot study for Limburg Province modelled air filtration services using established values for PM_{10} capture by different types of land cover, combined with ambient PM_{10} concentration maps (Remme et al, 2017). The value of PM_{10} capture was assessed using avoided air pollution-related health costs. Although these costs related to health service providers, the use of the ecosystem service was tentatively assigned to households as the primary user since they benefit from lower negative health effects from air pollution.

This work was extended to the whole of the Netherlands, incorporating values for a range of health impact categories, including days of lost work, new cases of chronic bronchitis, and respiratory and cardiac hospital admissions (Hein 2018). The resulting values were estimated to be significantly lower than equivalent welfare based valuations.

The UK. This study (Jones et al, 2017) based the physical flow account on the EMEP4UK atmospheric chemistry and transport model which generates pollutant concentrations directly from emissions, and dynamically calculates pollutant transport and deposition, taking into account meteorology and pollutant interactions. For the purposes of assessing the contribution of the ecosystem to the benefit, the role of vegetation in removing air pollution was assessed using a comparison of two scenarios 'current vegetation' and 'no vegetation' derived from the land cover map.

The health benefits were calculated from the change in pollutant exposure from the scenario comparisons, i.e. the change in pollutant concentration to which people are exposed. Damage costs per unit exposure were then applied to the benefitting population at the local municipal authority level for a range of avoided health outcomes: respiratory and cardiovascular hospital admissions, loss of life years (long-term exposure effects from $PM_{2.5}$ and NO_2), and deaths (short-term exposure effects from O_3). Changes in concentrations for other pollutants (PM_{10}, NH_3 and SO_2) were also modelled but not valued in monetary terms.

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