Forestry Commission

Research Report

Valuing the social and environmental contribution of woodlands and trees in England, Scotland and Wales

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Social and environmental benefits of trees and woodlands

Aims:

A structured review to support policy, decision making and natural capital accounting

Outputs:

- Report on the state of the evidence base
- Woodland Valuation Tool: Database of evidence

Method:

Ecosystem Services Approach

The role of nature in human wellbeing

The Natural Factory

Environmental Production

Human Economy

Goods and Services

Human Wellbeing

State of knowledge:

Evidence Base = Biophysical evidence + Valuation estimates + Decision support tools

	Biophysical evidence	Valuation estimates	Decision support tools
Biodiversity	✕	✕	✕
Air quality	/	/	/
Climate	✓	/	✓
Water	✕	✕	✕
Farm trees	✓	✕	✕
Physical and mental health	✕	✕	✕
Recreation	✓	/	✕

Key: ✓ Relatively strong evidence base; / Some evidence base; ✕ Gap in the evidence base

Critical research gaps:

- Greater understanding of the biophysical pathways between trees and goods and services
- An integrated, consistent and comprehensive approach to valuation
- Making the most of existing data
- Development of accessible decision support tools

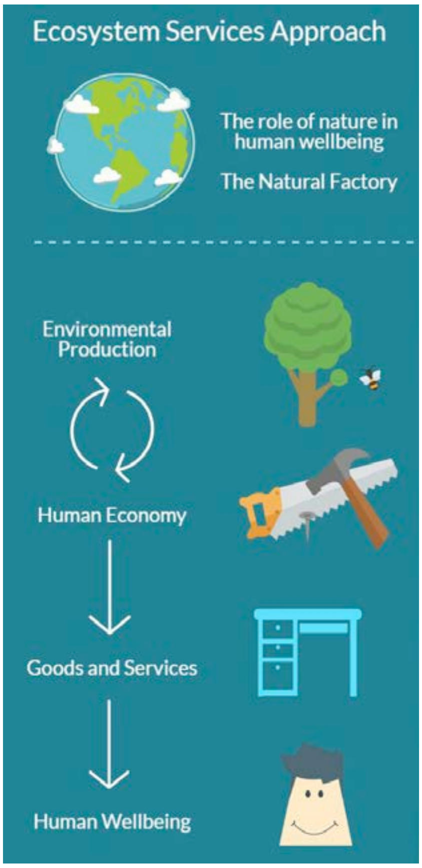
Executive summary

Introduction

The diverse resources provided by trees and woodlands contribute to the production of a wide array of benefits ranging from timber to wildlife habitats and from carbon storage to water purification. This diversity is further complicated by the fact that, while some of the goods associated with forests are traded in markets and hence have associated prices, others arise outside markets and, while valuable, lack prices. The need to make evidence-based decisions regarding woodlands, including decisions such as how much public funding should be allocated to support the non-market benefits they generate, has necessitated the estimation of the value of those benefits. This scoping study provides a structured review of the state of knowledge regarding the economic valuation of social and environmental benefits derived from trees and woodlands in order to support policy and practice. Particular (although not exclusive) attention is paid to recent extensions to the literature since previous reviews (especially Eftec, 2011).

In preparing this study, the research team at CSERGE undertook a structured review of how technical and methodological developments are transforming the potential for robust valuation of non-market benefits and allied decision-making. The methods, data and modelling techniques which underpin the existing evidence base on the value of woodlands and trees were critically evaluated so as to provide a practical set of actionable options for enhancing that evidence base and improving decision-making.

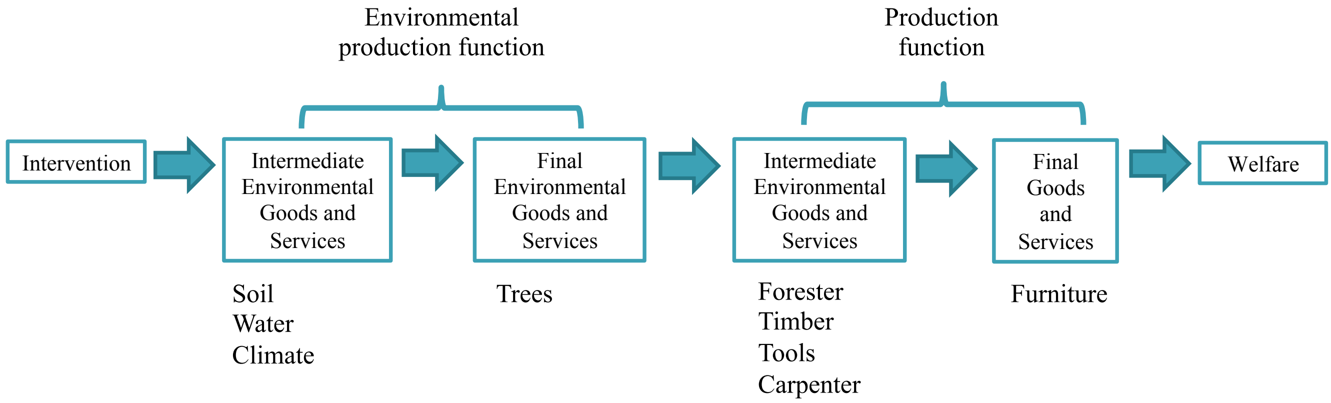
The benefits provided by trees and woodlands are methodically examined in the report using the ecosystem services approach. Unlike the 2005 Millennium Ecosystem Assessments classification, which divides ecosystem services into provisioning, regulating, supporting and cultural services, the ecosystem services approach establishes a structured method for valuing environmental and social benefits. The ecosystem services approach attempts to clearly identify and understand the pathways (and environmental production processes) that affect the provision of final goods and services and to acknowledge that economic value comes directly from the consumption of these final goods and services. For example, people derive value from a house but would find it practically impossible to disaggregate that value into the independent contributions made by individual inputs such as the bricks, timber and concrete that went into its construction. Likewise, a water company derives value from the purity of



the raw water it abstracts from the environment but has no direct perception of the value of the trees, soils and biotic community that contribute to the quality of that water. The ecosystem services approach is grounded in economic theory and provides a structured method for identifying how benefits are provided, who benefits and what value they place on these benefits.

The central idea behind the ecosystem services approach is to characterise the role of nature in delivering human well-being using the same concepts as are applied to describing the economy. In this sense, the environment can be characterised as a complex natural factory engaged in a myriad of productive processes. These natural productive processes[1] combine environmental inputs to produce final environmental goods and services, which have direct and immediate consequences for productive activities in the human economy. To understand the role of nature in delivering human well-being it is important to understand how these environmental production functions feed into the production activities of firms and households. A woodland-based example of these processes is captured in the diagram

[1] These productive activities of nature are described by environmental production functions and include processes such as the transpiration and the absorbance and deposition of particles.



above, which shows how a final good, furniture, is the product of environmental inputs such as soil, water and seeds from which trees are grown. Trees are an environmental good which feed into the human production functions to produce timber, using labour input from a forester. Timber is then crafted by a carpenter using tools to produce furniture which is sold on to consumers, who gain welfare from its use.

Conceptually, by adopting an ecosystem services approach the review builds upon recent developments that have sought to enhance the valuation evidence base through improving the integration of natural science, economic and social science methods. To achieve this, a good understanding of the biophysical pathways influencing the physical provision of goods and services that are heavily dependent upon the natural world is just as crucial for robust valuation as the contribution of appropriate economic methods.

Given the crucial importance of the natural environment in the generation of woodland benefits, this harmonisation of knowledge and approaches is considerably assisted by the conceptualisation of the environment as a stock of 'natural capital' (such as soil, air, water and living things) which generates flows of 'ecosystem services' that contribute to human well-being. These underlying principles are discussed early on in the report and frame the subsequent review.

The review itself considers the range of unpriced benefits associated with trees and woodlands. As part of this review we seek to highlight areas where the evidence base is incomplete or missing. Alongside gaps in the underpinning natural science base, we find a significant requirement to improve, standardise and integrate evidence regarding the value of the multiple benefits delivered by trees and woodlands. Building upon this, the scoping study culminates with a clear, prioritised set of realistically actionable options for enhancing the evidence base to generate valid, robust and comprehensive valuations of the social and environmental benefits of trees and woodlands.

Structure: report and Woodland Valuation Tool

The report is organised in sections which group together topics. Section 1 provides the conceptual framework for the report by developing the ecosystem services paradigm in relation to trees and woodlands (a detailed theoretical appendix is also provided to yield a comprehensive resource reference). The ecosystem services framework provides the structure for the other sections in the report. Sections 2 to 8 review the economic assessment of the impact of trees and woodlands on a wide range of values associated with water quality, water availability and flood alleviation, air quality, climate, recreation, physical and mental health, biodiversity and agriculture. Summaries at the head of each of these sections use a colour code to indicate the quantity and quality of evidence which currently exists. Section 9 addresses the issue of tree health and how this influences the social and environmental benefits provided by woodlands. Given that the majority of the population live in towns and cities, Section 10 reviews the existing evidence and decision-making tools relating specifically to urban trees. This is followed, in Section 11, by a critical assessment of the issues arising from the biophysical, economic and psychological differences between gains and losses in relation to trees and woodlands. Section 12 reviews recent innovations in integrated modelling and decision support tools while Section 13 explores current issues and debates in relation to natural capital accounting. Finally, Section 14 presents a prioritised list of research gaps and, where possible, suggestions for addressing these gaps.

The results of the study are also organised in a supporting 'Woodland Valuation Tool', developed in Windows® Excel. This enables users to search for and cross-reference appropriate methods and the existing literature relating to different goods and services, or by beneficiaries or various other categorisations related to trees and woodlands. The literature contained in the tool relates specifically to trees, woodlands and forests and as such is appropriate for use by analysts involved in forest management decisions.

However, the system has been set up to facilitate and encourage easy extension to consider other natural environment resources. The tool has been designed to be easy to use, multiplatform, accessible using open source software, and simple to update and extend. The tool is compatible with Microsoft® Excel v.2007 and above as this is a familiar and easily accessible program for the target users. All instructions are for Microsoft® Office 2013 but should be very similar in earlier versions.

Priorities

General critical research gaps

The results of the scoping study revealed a number of general critical research gaps which cut across several, if not all, of the research areas:

- Biophysical pathways: The scoping study explored both the existing biophysical literature and the valuation literature. Although we were generally able to find separate evidence relating to both biophysical processes and values, the usefulness of these existing studies is severely hindered by the absence of rigorous evidence linking the biophysical processes associated with trees to quantifiable changes in the provision of goods and services.
- Valuation literature: The existing literature is patchy, incomplete and uses a plethora of different units, years and scales. This makes a coherent approach to valuation extremely difficult, particularly because study design plays a large role in determining the valuation estimates. An integrated, consistent and comprehensive approach to valuing all of the benefits and costs associated with tree and woodland land use and management is needed.
- Making the most of existing data: There is an abundance of existing but fragmented data relating to social and environmental benefits. With advances in computing power and cross-disciplinary collaborations there is clear potential for these data sources to be brought together and used to develop sophisticated models for valuation. In order to achieve this, decision-makers will require access to the broad range of data available. In this vein, a new class of integrated ecosystem service mapping tools is beginning to emerge, including InVEST, LUCI, MIMES and The Integrated Model (TIM, developed by CSERGE). These tools incorporate biophysical models to reflect interactions between multiple ecosystem services at various spatial and temporal scales.

  For the purposes of policy-making and valuation TIM has certain advantages:
  - It contains an economic behaviour model, which shows how decision-makers (e.g. farmers) respond to changes in the market, policy and the environment. This allows the policy-maker to see how changes in policy, prices, regulation and so on affect land use and avoids the use of scenarios that do not explain how future land uses arise.
  - Alongside quantitative analyses of the integrated effects of land-use change, TIM also delivers economic values for these changes, allowing the policy-maker to conduct cost-benefit analyses of changes.
  - TIM contains an optimisation routine which allows policy-makers to explore the best way to achieve their objectives. The model also provides the ability to adjust the definition of what constitutes a 'best' outcome. Ongoing work seeks to examine issues such as the distributional implications of different decisions.
- Accessible decision support tools: There is a general need for the development of up-to-date, easy to use decision support tools. These tools need to be technically sophisticated enough to incorporate the most recent advances in data, methods and modelling, yet also amenable to use by non-analyst decision-makers following relatively brief (e.g. one week) training.

The study also allowed the identification of knowledge gaps specific to each benefit valuation area. Top priorities are summarised below and discussed in further detail within Section 14.

Water quality

- Biophysical pathways: Many valuation studies fail to link water quality outcomes to woodland management or planting actions. This makes it difficult to establish causality and limits the usefulness of existing studies for investment appraisal when the objective is to achieve specific improvements in water quality.
- Multi-impact, multi-scale valuation: There is a need to extend the valuation of different pollutants and their removal from waterways. This needs to be flexible in terms of the scale of analyses, embracing both catchment and national levels.

Water availability and flood alleviation

- Biophysical pathways: There exists a variety of evidence on the biophysical relationships between tree cover and water quantity (e.g. through modelling studies and to a much lesser degree through observed data at the catchment level). To fully quantify the effect of afforestation or deforestation, data are needed to validate models, especially at the catchment scale. The absence of robust biophysical evidence quantifying the relationship between local woodland management, location and forest design and changes in the quantity of water available constitutes a significant barrier to reliable valuation and decision-making, particularly as scale increases. There is also a gap in the evidence base in terms of the impact of

climate change and rising CO_2 levels on the water use of trees, which will affect the services (dis-services) provided in the future.
- Flood alleviation: The current literature linking trees and woodlands to the prevention of flooding is growing but due to the wide variety of other factors involved in flood events we are still some way off being able to fully quantify the effect of upstream tree planting or woodland management changes on the probability of downstream flooding.
- Integrated valuation of water: There is a clear need to integrate the variety of values associated with water resources and the role that woodlands can play in enhancing these.

Air quality

- Valuation and spatial proximity to populations: The health impacts caused by air pollution depend upon the number of people being exposed; a tonne of SO_2 in a densely populated area causes more damage than a tonne in a sparsely populated area. The value of pollution absorption by trees should reflect this population exposure.

Climate

- The Forestry Commission has a well-established model of carbon accounting called CARBINE (Edwards and Christie, 1981, see http://www.forestry.gov.uk/fr/infd-633dxb for further details). CARBINE estimates stocks of carbon stored in trees and released through harvesting as well as avoided greenhouse gas emissions (through the use of wood products that displace fossil fuel intensive materials), and these models can scale from individual trees to entire woodlands, taking into account a range of management practices, such as thinning and felling.
- The nature of carbon as a perfectly mixing pollutant means that the value of one tonne of carbon sequestered does not depend on the location of the sequestration. This allows the social cost of carbon to be applied with ease.
- Economic valuation: Improved estimates of the social cost of carbon/abatement costs (carbon price). This is an active area of research, but is unlikely to be resolved in the short or medium run. Employing UK Government carbon prices is a straightforward compromise which would allow current research efforts to focus on higher priority issues.

Recreation

- Decision support tools: Research has the potential to substantially improve decision-making in this area. Improved decision-making tools are needed to support urban planning and the management of recreational sites.

Physical and mental health

- Measurement challenges: There is no commonly applied generic measure for mental health. This makes comparison between biophysical studies difficult and the lack of a well-defined and commonly understood mental health good or service poses a challenge for valuation. A more fundamental challenge is the need to establish causality, substitution and response behaviours between trees/woodland (as opposed to other environments) and mental and physical health. So, for example, if new woodlands generate visits, to what extent are these genuinely additional visits as opposed to substitution away from other activities? To what extent are there net health gains? Does enhanced engagement with nature generate positive or negative co-impacts (e.g. does outdoor exercise stimulate improved mood or give individuals a perceived licence to indulge in other unhealthy lifestyles).

Biodiversity

- Economic valuation: The requirement for improvements in the economic valuation of biodiversity needs to be matched by better data and natural science understanding of the physical impacts of afforestation upon measures of biodiversity. In both the UK NEA and UK NEAFO analyses biodiversity was assessed through bird species indices. This approach was adopted due to the relatively poor cross-sectional and time-series data available for wider measures of biodiversity, a factor which marks out a significant research gap for future assessments. Similarly, understanding of the relationships between woodland biodiversity and human health requires more accurate and quantified assessment of the underpinning physical pathways of effect than is currently available. A particular problem arises regarding estimation of the non-use benefits of biodiversity where the lack of behavioural action precludes the use of revealed preference methods.

Trees and woodlands on farms

- There is a need to understand the biophysical links between trees and woodlands and agricultural output, in particular spatial and temporal differences as well as the relative merits of different species and management practices. For example:
  - Understanding the importance of the species, age and location of trees on farms for the provision of soil stabilisation, particularly in the context of an increase in the frequency of extreme weather events due to climate change.
  - Research on the importance of habitat configuration and connectivity to support biodiversity, and conversely to reduce risks from pests.
  - A deeper understanding of the relationship between different species and management practices, different pollinators and their combined impact on agricultural yields.

Plant (tree) health

The evidence base on the impact of tree health on the value of the benefits provided by trees and woodlands is small but emerging. There remains a substantial need for research in this area, in particular to address difficulties in understanding the counterfactual – what would have happened if the trees were healthy.

Urban trees

Analysis was also carried out of the evidence and knowledge gaps with regard to urban trees.

Water resources

- i-Tree Eco provides a useful resource for estimating the impact of urban trees and woodlands on storm water drainage. However, since the hydrological models were developed in the USA and are closed within i-Tree Eco it is difficult to assess the transferability of the model to the UK setting.
- There is limited existing information on the relationships between urban trees and water quality, including their role in reducing sewage treatment costs and improving urban recreation. Estimates of the impact of urban trees on water resources at recreational sites and the resultant impact on the value of recreational visits could be constructed by using general biophysical studies on the impact of trees on water quality and valuing the impact of the change in water quality on recreation, taking into account the location of the recreation site (allowing for distance decay and proximity to population).
  Adopting this approach requires an implicit assumption that the biophysical process is the same in urban and rural areas, or that any important scaling factors (such as tree density, nutrient concentration, flow rates and distance from sewage works) were represented in the sampled data and have been controlled for.

Air quality

- The literature relating urban trees to air quality suffers from the same limitations as for water resources. Although there are simulation models relating individual tree species (controlling for maturity) to air filtration (Donovan *et al*., 2005), these models are based on underlying biophysical studies which sample larger woodlands (greater than 2 ha). Moreover, there is uncertainty over the rates of absorption and deposition and there is very little discussion of whether these rates are likely to be the same in urban and rural areas (Powe and Willis, 2002, 2004).

Health values

- The key challenge in valuing the physical and mental health benefits provided by urban trees and woodlands lies in developing a clear understanding of the biophysical processes at work.
- There is some existing evidence on the physical health benefits provided by trees and woodlands; there are studies linking greenspace to exercise and physical health, and evidence of links between trees and water quality, air quality and climate (see Sections 2, 3 and 4 for further details). The challenge in this area is to understand whether these relationships hold, or are augmented, for urban trees as a subset of greenspace.
- Evidence on the mental health benefits provided by trees and woodlands is undergoing substantial but slow development. A major challenge in this area is presented by the need for a common generic and comparable metric for measuring mental health. In addition, the existing evidence is often highly localised and difficult to interpret without a suitable control study. A major gap in this area is the development of rigorous, generalisable and comparable studies of the biophysical processes.
- The Health Economic Assessment Tool (HEAT) is available from the World Health Organization Regional Office for Europe. HEAT provides values for the benefits derived from habitual walking and cycling as recreational activities using the UK Value of Statistical Life discounted using a default discount rate of 5%.[2] However, the tool does not disaggregate the benefits by particular types of green infrastructure. As a result, reporting the total value will overstate the benefits from urban trees and woodlands, but alternatively scaling for the proportion of total green infrastructure that is trees and woodland makes the assumption that green infrastructure is perfectly substitutable.

Climate

There is significant evidence for the climate-related benefits of urban trees and woodlands.

- There is a broad literature on the biophysical processes and economic values related to urban cooling services by shade trees in the USA (Akbari, 2002; Nowak *et al*., 2010, 2012). Using data on indoor and outdoor temperature and humidity, wind speed and direction and air-conditioning cooling energy use, Akbari *et al*. (1997) show that shade trees near houses can yield seasonal cooling energy savings of approximately 30%. Given the relative temperatures and prevalence of air conditioning in North America relative to the UK, it is possible that energy savings

[2] Users are able to override this default value; we recommend using the official UK Treasury procedure for discounting.

may be lower in the UK. However, if future studies also incorporated potential health impacts (of reducing urban heat islands during summer heatwaves, reduced dehydration, heat stroke), the overall value of urban cooling services from trees could remain substantial.

Recreation

- Urban trees and woodlands provide opportunities for recreational experiences in an urban landscape, which is a mosaic of different land uses and in close proximity to densely populated residential and commercial areas. The evidence for recreational values from urban trees and woodlands is relatively robust (Brander and Koetse, 2011; Perino *et al*., 2014); however, none of the urban valuation tools reviewed here currently incorporate recreation into their valuation calculations.
- Bateman, Abson *et al*. (2011) and Bateman, Day *et al*. (2014) show how location of recreational sites matters. A recreation site can generate a significant range in values depending on where it is located. The critical determinant of this range is, perhaps not surprisingly, proximity to significant conurbations; thus the study of recreation values in urban areas is particularly salient.

Biodiversity

- Johnston, Nail and James (2011) discuss the debate among urban forest professionals regarding the role of exotic versus native tree species and their contribution to urban biodiversity in Britain. They assess the current evidence and conclude that an automatic preference for native species cannot be justified, and that biodiversity and the wide range of services provided will be restricted by just selecting from the few native species that thrive in urban environments.
- Croci *et al*. (2008) suggest that effective management of urban woodlands could be a good option for promoting biodiversity in towns, and Davies *et al*. (2009) and Cameron *et al*. (2012) suggest that domestic gardens also provide an important contribution to UK biodiversity habitat and hence conservation. What is important in management and new planting decisions is a scientific understanding of the roles of particular species and the complex interactions in urban ecosystems.

Generic issues

The scoping study also revealed a number of generic issues and challenges facing the valuation of social and environmental benefits of woodlands.

Gains and losses

- The valuation of recreational benefits (costs) from incomplete gains (losses) presents a notable gap in the existing literature. This presents a challenge if we believe that the value of woodland recreation sites is related to the quality of trees at the site (e.g. species type, canopy size, tree density and tree health). There is little evidence to support or negate this; however, it seems possible that tree diseases with physical symptoms will affect the value of recreational visits. With the number of tree disease incidents rising, this is an area of increasing interest and concern.

Integrated modelling and valuation

- Perhaps the most fundamental research gap concerns the need to integrate natural science, economic and social science understanding of the multiple net benefits provided by changes in the extent and management of trees and woodlands in the UK. The current incomplete and fragmented science and valuation literature suggests that the diversity and integrated nature of woodland benefits leads to their systematic under-reporting. This in turn is likely to result in under-investment and substantial foregone values. A comprehensive extension to our understanding of these issues is therefore a significant priority for decision support.

Natural capital accounting

Accounting for woodland assets and related flows of ecosystem goods and services raises many of the same challenges encountered when accounting for other components of natural capital. However, the unique functions and characteristics of forest and woodland assets, the way they are managed and the types of services they provide mean that special consideration is required in a number of areas. The current research gaps include:

- Addressing spatial dimensions of woodland assets: In most instances, accounting systems do not need to incorporate a high degree of spatial detail. For instance, the System of National Accounts (SNA) records the same value for the sale of a chocolate bar whether that transaction takes place in London or Manchester. However, the market and non-market value of services generated by forests and woodlands can vary substantially over distances as small as 1 km. Spatial configuration, connectivity, overlap with other ecosystems and natural capital assets (e.g. lakes and rivers) and distance from human populations are important determinants of the value generated by woodland assets. Location and spatial configuration determine the provision of flood defence services, connectivity has implications for wildlife habitats and susceptibility to pests and diseases, overlap with lakes and rivers has implications for the supply of water purification services, and distance from human populations impacts recreation values. Depending on the intended policy uses of woodland natural capital accounts, some or all of these spatial dimensions may need to be included.[3]

- The importance of mapping and physical accounting: Closely related to the spatial dimensions mentioned above, accurate biophysical data are crucial for identifying and understanding trends in ecological function, for designing management responses and for assessing the impact of environmental and policy change. Moreover, they are a necessary first step for developing monetary natural capital accounts. One key issue, also related to spatial dimensions, is the scale at which maps and biophysical data are collected and organised. Depending on who is developing the accounts, and for what purposes, appropriate scales might include watersheds and river catchments, land-use categories, or administrative boundaries.
- Estimating marginal vs. stock values: Most environmental valuation methods are designed to estimate the value of small (marginal) changes rather than large (stock) changes. This is appropriate for most decision-making purposes (including project appraisal and investment decisions), where for example it may be necessary to value the likely impact of afforesting or deforesting a specific unit of land without having a significant effect on the country's total woodland stock. The values estimated in such instances are marginal in that they represent a relatively small change when compared to the UK's total stock of woodland. However, those marginal values are unlikely to remain constant when we consider large-scale changes in the stock, where increasing scarcity rents and threshold effects may need to be incorporated.
- Ecological tipping points, resilience and functional redundancies: One of the greatest obstacles to valuing forest assets is our incomplete scientific understanding of ecosystem resilience, the existence, location and severity of threshold effects, and the extent to which functional redundancies exist within an ecosystem. Over time, improved scientific understanding and new data collection may provide useful insight. However, until then, risk registers based on existing information (Mace *et al*., 2015) may assist in identifying trends, defining meaningful metrics to describe asset–benefit relationships, and identifying assets under the greatest pressure.

Key concepts for understanding economic valuation

- Valuation reflects the benefits people derive from the natural environment. It does not attempt (and cannot be used) to assess the preferences of non-humans other than in how they affect human values. Values are determined by human preferences, which are subjective; as human preferences change, so do the values placed on goods and services. This may be driven by social and cultural context, public opinion or changing technologies.[4] Valuation incorporates these changes.
- Scientific underpinning is central to economic valuation which relates biophysical changes to impacts on human welfare, measured in monetary terms. Thus, economic analysis is only ever as good as the natural science on which it is based.
- Economic value has been criticised because it fails to add on separate elements that record shared or communal values (defined as values that are enjoyed by a community rather than an individual) and other-regarding values (values derived from benefits that accrue to others). To economists, those criticisms appear ill-founded. For a start, a community is not an entity that can experience well-being independent of the humans from which it is constituted. Those humans may experience different levels of economic value as a result of being part of a community but that additional value will be captured by their own expressions of economic value. Likewise, if an individual's sense of well-being is in part determined by the well-being experienced by others then that other-regarding value will also be reflected in their expressions of economic value.
- Prices and values are not the same. While public parks may be unpriced at the point of use, they clearly have value to people. Economic analyses assess these values to help inform decisions. Valuation is not an attempt to commoditise nature.
- Economic values are typically expressed in monetary units. A unit of monetary value is worth the same regardless of its origin, meaning environmental costs and benefits should be considered on par with the myriad of competing demands on government budgets. In principle, this means that monetary units can be compared like for like; for example, GBP 1 of biodiversity benefits has the same value as GBP 1 of timber.

[3] The SEEA-EEA (2014) identifies three scales of analysis for ecosystem accounting:
1. Basic spatial units (BSUs): tessellations (grid squares) of for example 1 km^2 or cadastres (land polygons of varying shapes reflecting things such as ownership).
2. Land cover/ecosystem functional units: a contiguous set of BSUs constituting a particular type of land use or ecosystem.
3. Ecosystem accounting unit: a larger scale/fixed area taking account of natural features (e.g. topography and river catchments) and/or administrative units and boundaries (e.g. national parks).

See also, Eftec (2015).

[4] For example, cultural shifts in preferences can be seen in the rise of interest in wilderness areas (Nash, 2001) while technology shifts have in part been responsible for a resurgence in the use of fuelwood (Couture, Garcia and Reynaud, 2012).

- Economic valuation is not the same as environmental accounting. Valuation assesses the impact on human well-being (the value) of marginal changes in the provision of environmental goods and services. In contrast, environmental accounting attempts to measure natural capital stocks so that annual changes and trends over time can be identified.

1. Ecosystem services: the paradigm and its terminology

An extended version of this section is provided in Annex 1. Interested readers may refer to the Annex and progress to Section 2 without loss of information.

The human economy

Understanding the contribution trees and woods make to human well-being is not a straightforward undertaking. Trees and woods impact on the environment in a multitude of ways that, through a multitude of pathways, benefit a multitude of people in a multitude of ways. The ecosystems services approach provides a framework within which we can simplify this complexity and organise our thinking when approaching the task of valuation.

Central to the ecosystem services approach is the idea that we can characterise the natural world as a production system, a production system akin to those that we observe in the human economy. In the human context, perhaps the most familiar production system is that organised by a firm. Put simply, a firm gathers together various inputs in order to produce one or more outputs. In the language of economics those outputs are termed 'goods and services'. Actually, economists distinguish between two forms of goods and services:

- An intermediate good and service is one that is sold on to another firm and acts as an input to the other firm's productive activity.
- A final good or service is one that is sold on to consumers, who gain welfare from its consumption.

That final point is worth reiterating. Human welfare is enhanced by the consumption of final goods and services. Intermediate goods and services do not generate welfare in and of themselves; they only contribute to the economy's ability to produce final goods and services. For example, timber, an intermediate good produced by a lumber company, is not a direct source of well-being for humans in and of itself. Along with other intermediate goods and services including skilled labour and carpentry tools, however, timber can be fabricated into a table – a final good from which humans do derive well-being.

In addition to the productive activities of firms, economists recognise a second form of productive activity; that undertaken by households. The idea here is that the service flows from which households actually gain welfare are generated through individuals using their time and money to combine a particular set of final goods and services. So, for example, the benefit gained from watching a film at the cinema arises through the household combining travel, time and a cinema ticket; take any of those ingredients away from the household production process and the household gains no welfare.

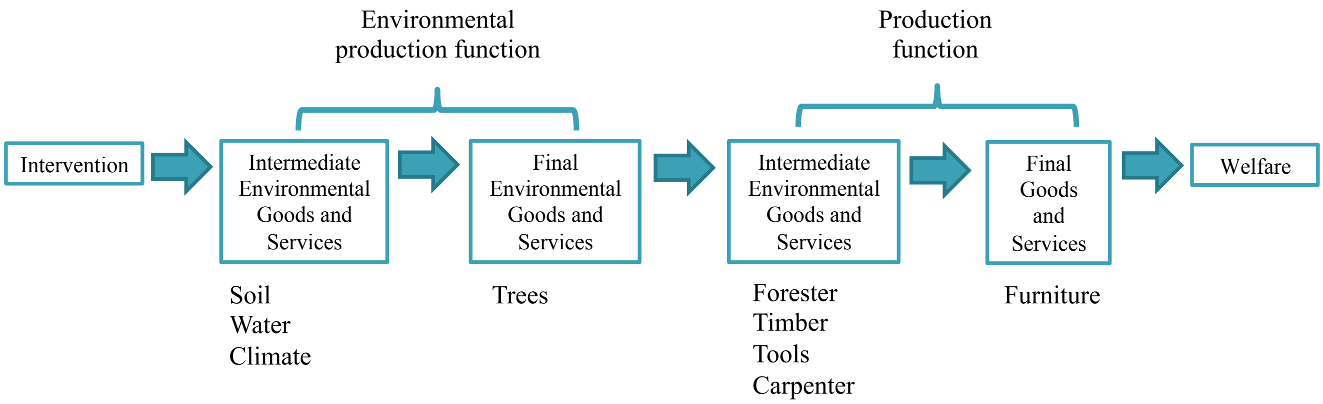
Accordingly, our simple way of understanding the workings of an economy is to imagine households and firms engaged in productive activities. Those activities involve making use of a variety of goods and services in order to produce an output. The relationship between the use of inputs and the creation of outputs is described by a production function, where the term household production function is used to distinguish household productive technology from that of firms.

The natural factory

The central idea behind the ecosystem services approach (Figure 1.1) is to use the same concepts in order to structure our understanding of the workings of the natural world. In a nutshell, the ecosystem services approach characterises the environment as a complex natural factory engaged in a myriad of productive processes. Of course, unlike the productive activities of firms and households, the productive processes in the environment are not organised by humans but arise spontaneously in nature; indeed, that is their defining characteristic. In an exact parallel to the human economy, the productive activities of nature are described by environmental production functions. Just like their human-controlled counterparts, environmental production functions require inputs and deliver outputs. In parts of the literature, particularly outside economics, these outputs are called ecosystem services. For a number of reasons we prefer to use the more inclusive term environmental goods and services.[5]

[5] First, environmental production functions span a range of natural processes that may be physical (e.g. coastal erosion) and chemical (e.g. low-level ozone generation) in nature as well as ecological. The emphasis placed on ecological functions by the term 'ecosystem services' is arguably somewhat narrow and may cause confusion given the important contributions of abiotic resources to human well-being. Second, environmental production functions can result in both tangible and intangible outputs. To an economist it would seem more appropriate to refer to tangible outputs as 'goods' rather than services.

Figure 1.1 The ecosystem service approach.



Notice the clear distinction in this terminology between the process and the output. To be perfectly clear: environmental production functions are to flows of environmental goods and services as economic production functions are to flows of goods and services (Brown, Bergstrom and Loomis, 2007). For example, water purification is not an environmental good/service. Rather, it is the environmental production function that delivers the environmental good/service of pure water.

Final and intermediate environmental goods and services

Another crucial distinction clarified by the ecosystem services characterisation of nature is between intermediate and final environmental goods and services (Boyd and Krupnick, 2009).

- Intermediate environmental goods and services (IEGS) are environmentally produced goods and services that act as inputs to some other environmental process.
- Final environmental goods and services (FEGS) are environmentally produced goods and services that enter household or firm production functions without further biophysical translation. In other words, FEGS are those particular subsets of environmental goods and services that have direct and immediate consequences for productive activities in the (human) economy.

This distinction is particularly important in the context of valuing the contribution of nature to human well-being. In particular, households and firms perceive value as resulting from the flow of FEGS that they enjoy. While the supply of those FEGS is underpinned by environmental processes that draw on a variety of IEGS, people do not have preferences for IEGS any more then they have preferences for intermediate economic goods and services. For example, people derive value from a house but would find it practically impossible to disaggregate that value into the independent contributions made by the bricks, timber and concrete that went into its construction. Likewise, a water company derives value from the purity of the raw water it abstracts from the environment but has no direct perception of the value of the trees, soils and biotic community that contribute to the quality of that water.

In practical terms, the distinction between FEGS and IEGS is critical. It identifies the fact that attempts to value the environment must focus on FEGS since households and firms can meaningfully deduce the benefit they derive from those environmental goods and services. In contrast, the value derived from IEGS is not immediately apparent to households and firms. In understanding the value provided by IEGS, an extra step is required which first determines the contribution those IEGS make in terms of delivering FEGS.

The distinction between IEGS and FEGS is not always straightforward. The same environmental good or service may act as an input to both human and environmental production systems. For example, pure raw water is a FEGS for water supply companies who extract it from rivers and reservoirs, but it is also an IEGS to the environmental production process through which freshwater fish reproduce (the output of which is fish that might act as a FEGS in the human activity of recreational fishing).

A further source of confusion is the fact that what some people refer to as ecosystem services actually arise from processes that are not naturally occurring; for example, food from agriculture or timber from a plantation forest. Both these goods and services result from human-organised production processes which require significant inputs of produced capital and labour on top of crucial inputs of FEGS from nature including soil, rainfall, sunshine and pollinators.

Natural capital

Another complicating factor is the fact that the environment can store environmental goods and services as stocks of natural capital. Unfortunately, the term natural capital is increasingly used interchangeably with the term ecosystem services, though there are important differences between the two. Most importantly, natural capital is a stock that can persist from period to period while environmental goods and services are flows that are generated by some environmental production process over a period. Of course those flows have to go somewhere; environmental goods and services are either consumed in some other production process (human or environmental) or accumulate in the form of a natural capital stock.

A further distinction that one may want to draw in this regard is between capital stocks and inventory stocks, a distinction that distinguishes between how capital is used in productive processes. In particular, the productive value of inventory is realised through liquidation but that of capital is not. Capital is undiminished in quantity or quality through its use in production. It follows that it is not the nature of the physical stock which determines whether it is capital or inventory, but the nature of the production function that exploits that stock. Indeed, the same physical stock can be both capital and inventory if it enters different production functions. For example, a stock of trees is natural capital in the environmental production function that produces habitat for wildlife (the tree stock is not diminished in the process of generating wildlife). In contrast, that same stock is natural inventory in the economic production function that harvests timber for human consumption (the tree stock is diminished as part of this production but can be managed sustainably or allowed to regenerate naturally).

The welfare implications of environmental interventions

The primary purpose of the ecosystems services paradigm is to provide a framework within which the welfare implications of an environmental intervention might be appraised. By an environmental intervention we mean any project or policy that has impacts on the natural environment. In the simplest case, such an intervention might just reduce the quantity or quality of flow of a FEGS. The task of evaluating that change is relatively straightforward; all an analyst requires is an estimate of the value that households or firms attach to that change in supply of a FEGS. How those values are established is a subject we shall return to on page 22 and Annex 1.

More often than not, however, the impact of an environmental intervention is to perturb some environmental production process. In that case, appraisal becomes more difficult. An analyst must first turn to the natural sciences to understand how the perturbation brought about by the intervention impacts on the output of FEGS from that process. Once that relationship is established the welfare impact of the intervention can again be established by applying estimates of the value that humans attach to that change in supply of FEGS. Of course, things get more complex yet if the perturbed environmental process results in outputs of IEGS that in turn feed into other environmental production functions. In that case, analysts require even greater input from natural scientists; the welfare impacts of the intervention can only be determined by tracing the impacts of that intervention through the natural factory and establishing the resulting changes in supply of perhaps multiple FEGS.

By way of example, imagine a planned intervention looking to establish continuous cover forestry on an area of woodland previously managed as a conventional clearfelled plantation forest. That management change has a number of effects. For example, by averting clearfelling it increases the supply of the FEGS 'visual amenity', a benefit that is enjoyed by humans that take pleasure from beholding an intact forest in the landscape in which the woodland is located. In this case the relationship between intervention and FEGS is pretty much direct. We simply require a measure of the added visual amenity value of continuous cover forest when compared to clearfelling.

A more complex consequence arises from reductions in soil erosion when switching from clearfelling to continuous cover. According to the ecosystem services paradigm, it is the consequent impacts of reduced soil erosion (through the natural factory on the delivery of FEGS) that delivers welfare improvements, not the reduction in soil erosion, which is an intermediate service. For example, eroded soil might be transported overland to watercourses and be deposited as sediment in a downstream reservoir. In this case, the FEGS is the rate of deposition of sediment in the reservoir, a good (or more correctly a bad) perceived by the reservoir's managers when considering their requirements for dredging. Here the analyst must establish the natural science that links continuous cover forestry with reduced rates of sedimentation. The value of the intervention in this regard is the reduction in costs associated with dredging.

Valuing final environmental goods and services

A number of attributes determine the value of final environmental goods and services. These include:

- Characteristics: These are the nature of the FEGS as it is delivered by the environmental production function. They are the dimensions of the FEGS that are recognised by humans and determine the value they attach to that supply. One can think about them as the units in which that FEGS is measured.
- Context: The value of the FEGS is not only determined by the way in which it is produced but also by the way it is consumed. We must understand how that FEGS fits into a perhaps complicated human production function that has many other arguments. We describe the current levels of those other arguments as context.
- Aggregation: How many people enjoy value and how this is mediated by proximity?

While most of the externalities generated by forests are positive, some are negative, for example, a reduction in water availability provides flood alleviation and reduced siltation but also imposes a negative impact upon water companies and their customers. To understand the net effect on society (i.e. to a broader set of beneficiaries), all externalities should be considered simultaneously, including impacts upon recreation, views, biodiversity, health and non-use values.

Production functions related to trees and woodlands

Throughout this report we organise the social and environmental benefits provided by trees and woodlands, and the economic production functions that they enter, into categories. To provide consistency these categories were based on the US EPA classification, as presented in Landers and Nahlik (2013). The full set of categories is summarised in Table 1.1, where crosses indicate the areas in which there is evidence that trees and woodlands provide benefits (or costs). Tables 1.2 and 1.3 provide descriptions of the categories.

Table 1.1 Categorising the social and environmental benefits of trees and woodlands.

Final environmental goods and services	Production functions																	
	Timber products	Food (agriculture and subsistence)	Industrial production	Pharmaceuticals	Hydropower	Drinking water	Transportation	Flood alleviation	Urban heat islands	Carbon sequestration	Housing	Physical health	Mental health	Recreation	Artistic	Learning	Spiritual and cultural	Non-use value
Water quality		✘	✘		✘	✘	✘				✘	✘		✘	✘	✘	✘	✘
Water quantity		✘	✘		✘	✘	✘	✘			✘			✘	✘	✘	✘	✘
Air quality			✘															
Climate		✘	✘					✘	✘	✘	✘	✘		✘				
Flora, fauna and fungi	✘	✘		✘							✘	✘	✘	✘		✘	✘	✘
Environmental amenity											✘	✘	✘	✘	✘	✘	✘	✘
Sound and scent											✘	✘	✘	✘	✘	✘	✘	✘
Views			✘								✘		✘	✘	✘	✘	✘	✘
Soil		✘	✘								✘			✘		✘	✘	✘
Timber and fibre	✘	✘	✘	✘							✘			✘	✘	✘	✘	

Table 1.2 Description of final environmental goods and services categories.

Final environmental goods and services categories	Description
Water quality	The condition of water in terms of its chemical, physical, biological, radiological and/or aesthetic characteristics
Water quantity	The volume and flow of water
Air quality	The condition of the air including chemical composition (e.g. NO_X, SO_2 and scent)
Climate	Temperature, rainfall and greenhouse gas concentrations
Flora, fauna and fungi	Plant and animal life
Environmental amenity	Characteristics of the surroundings and/or conditions in which a beneficiary lives, works or recreates
Sound and scent	Sources of sounds and scents as well as the magnitude of the emission
Views	Visible characteristics in which a beneficiary lives, works or recreates
Soil	Measures of the condition of the soil including soil type (e.g. clay, loam, sand), acidity (pH), moisture
Timber and fibre	Measures of the direct timber and fibre produced by trees and woodlands

Table 1.3 Description of production function categories.

Production function	Description
Timber products	The physical timber and fibrous material. This includes timber for extraction (e.g. wood for construction, fuel) and timber used for subsistence (e.g. wood for construction, fuel).
Food (agriculture and subsistence)	The edible substances as well as indirect benefits (e.g. pollination). This includes the extraction of edible substances from trees or woodlands both commercially and for subsistence (e.g. mushrooms, fruits, nuts) and indirect benefits, such as habitat for healthy populations of pollinators or trees providing shelter for crops.
Industrial production	The benefits trees provide to commercial and industrial businesses. This includes the impact on water and the atmosphere, for example providing industry with the opportunity to discharge waste.
Pharmaceuticals	The medicinal products and inputs. This includes the extracted wood, bark, roots, leaves, flowers, fruits or seeds used in medicines.
Hydropower	The benefits trees provide through the impact on the water environment for hydroelectric power producers.
Drinking water	The benefits trees provide through the impact on the water environment for water suppliers.
Transportation	The benefits trees provide through the water environment for the transporters of goods or people.
Flood alleviation	The benefits trees provide through the water environment for the alleviation of floods.
Urban heat island	The benefits trees provide in terms of shade, temperature regulation and energy savings.
Carbon sequestration	Carbon storage and sequestration, and greenhouse gas emissions.
Housing	The benefits trees provide to residential households. This includes the benefits through the impact on water and the atmosphere (including health benefits), opportunities for recreation and amenity value.
Physical health	The benefits trees provide to the physical health of the population through improvements in air quality, water quality, opportunities for exercise and so on.
Mental health	The benefits trees provide to the mental health of the population.
Recreation	Opportunities for recreation activities. This includes nature viewing (e.g. bird watching), hiking, and the opportunities to experience views, sounds and scents.
Artistic	Opportunities for amateur and professional artists. This includes the use of the environment to produce art such as the opportunities to experience views, sounds and scents.
Learning	Opportunities for educators, students and researchers to learn from and experience the environment.
Spiritual and cultural	The benefits trees provide for spiritual, ceremonial or celebratory purposes.
Non-use value	The benefits trees provide for people who care about existence value of the environment (those who think it is important to preserve the environment for moral/ethical connection or fear of unintended consequences) or bequest values (those who think it is important to preserve the environment for future generations).

2. Water resources

Trees and forests provide a variety of water-regulating services (and in some cases dis-services) which can be broadly divided into services affecting the quality of waterways and those affecting the quantity and flow of water. These services provide benefits to a variety of beneficiaries and valuing them requires an understanding of the biophysical processes at work, the relevant units of measurement and the specific beneficiaries. The two main subsections here divide water resources into these two broad categories of quality and quantity and review the existing evidence base for valuing them both. Our presentation is structured around the ecosystem framework approach, relating woodlands to the final environmental goods and services they yield and the various production functions that were identified by the steering group as priority issues.

While many studies focus directly upon water quality protection benefits, others incorporate water quality within a suite of benefits (arising from say, the conservation of greenspaces, recreation opportunities, biodiversity and habitat preservation and environmental education), or relate it to broadly defined 'environmental programmes'.

Water quality

Biophysical evidence	Valuation evidence	Decision support tools	Urban tree literature
Many studies fail to link water quality outcomes to woodland management or planting actions. This makes it difficult to establish causality and limits the usefulness of existing studies for investment appraisal when the objective is to achieve specific improvements in water quality.	There is a need to extend the valuation of different pollutants and their removal from waterways. This needs to be flexible in terms of the scale of analyses embracing both catchment and national levels.	The evidence base needs to be developed to facilitate the development of accessible decision support tools that incorporate water quality.	There is limited existing information on the relationships between urban trees and water quality (e.g. their role in reducing sewage treatment costs and improving urban recreation).

Key: Strong evidence; Good evidence but some gaps; Major gaps in evidence

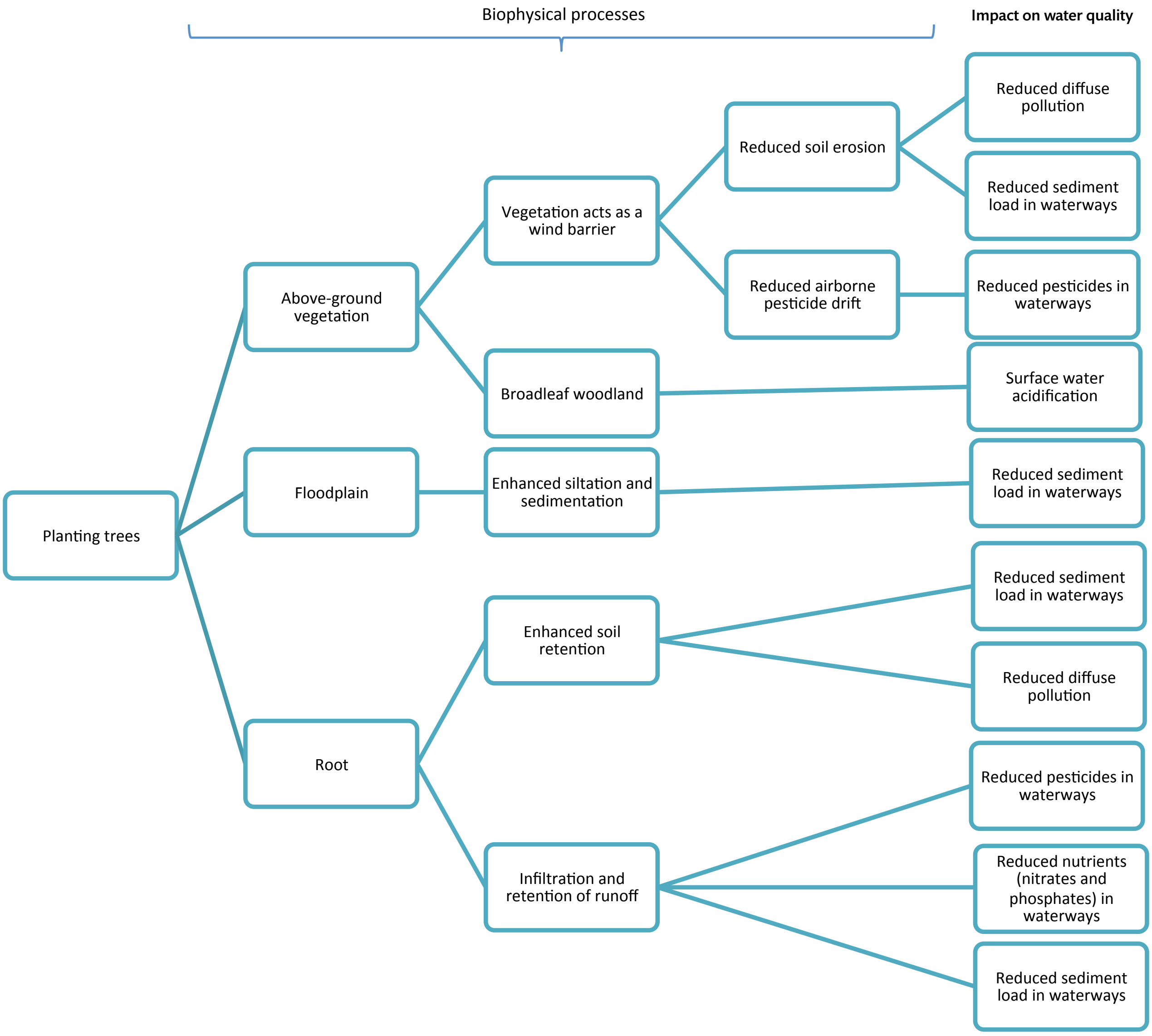
Biophysical pathways

Trees and woodlands impact on water quality through a number of pathways, as illustrated in Figure 2.1.

Examples of these biophysical pathways include:

- By providing above-ground vegetation trees act as a wind barrier, which reduces wind erosion, stabilises sand dunes and reduces the loss of topsoil into waterways (Nisbet, Orr and Broadmeadow, 2004). Riparian woodland has been found to be particularly efficient at intercepting aerial drift of pesticides and trapping pesticides bound to sediment in runoff (McKay, 2011). Both mature managed woodland and newly restored woodland have been shown to achieve pesticide reductions in studies, and in some cases this reduction can be substantial (Vellidis *et al*., 2002). There is also evidence to suggest that woodland can affect water quality negatively; for example, coniferous (Nisbet and Evans, 2014) and broadleaf (to a lesser extent) woodland expansion have both been associated with stream acidification (Gagkas, 2007; Gagkas *et al*., 2011; Ryan *et al*., 2012). The effects depend on tree species and acid sensitivity but in general are strongest where tree density is high. Floodplain and riparian woodland can reduce diffuse pollution by enhancing siltation and sediment retention (Jeffries, Darby and Sear, 2003; Nisbet *et al*., 2011) and nutrient removal (Gilliam, 1994). In addition, studies have found that the shade provided by riparian trees can significantly reduce peak summer temperatures in rivers and streams and may therefore have an increasingly important impact on algal blooms and freshwater biodiversity (Broadmeadow *et al*., 2011).
- Below ground tree root networks can stabilise banks preventing erosion, especially near to waterways where they typically reduce the amount of sediment entering rivers. Reducing sediment runoff has both direct benefits,

Figure 2.1 Biophysical processes of woodland influencing water quality.



such as improving conditions for fish breeding (Carling *et al*., 2001), and indirect benefits, for example by reducing some forms of nutrient runoff as phosphates bind to soil particles which may then be transported into waterways (Hutchings, 2002).

Final environmental good or service

The final environmental good is changes in water quality attributed to woodlands. These goods and services are presented in the 'impact on waterways' section of the biophysical pathways in Figure 2.1.

There is strong evidence to suggest that well-located woodland planting can lead to improvements in both surface water quality (Calder *et al*., 2008) and groundwater quality (Yamada *et al*., 2007). These improvements include the uptake of excess nutrients such as nitrates and phosphates; the interception and reduction of pesticide concentrations and sediment runoff and temperature regulation (Broadmeadow *et al*., 2011; Nisbet, Silgram *et al*., 2011); however, trees have also been linked with negative impacts including increased acidification from coniferous trees (Nisbet and Evans, 2014).

Water quality units

The extant literature defines water quality in a range of ways, using information on metrics such as the concentration of sediments; nutrients, including nitrates and phosphates; pesticides; the proportion of water that requires treatment; and classifications such as the Water Framework Directive's ratings for ecology, aesthetics and riverbanks. Which unit is most appropriate for any given study or valuation depends on how the change in water quality flows through various production functions to affect specific beneficiaries. Many studies value the changes in specific units (e.g. nitrate in mg l^{-1}, temperature in degrees Celsius, and sediment in mg

l^{-1}) whereas others assess changes between broad categories of water quality (e.g. pristine, good, fair, poor). Particularly for assessing recreational values, the latter approach enables researchers to relate physical units to those relevant for measuring recreational values, for example in revealed preference (travel cost) studies (e.g. Bateman, Day *et al*., 2014) or stated preference surveys allowing visitors to convey preferences for water quality without specific reference to detailed scientific measurements which are unlikely to be understood by the public (e.g. Bateman, Brouwer *et al*., 2011).

Economic production functions

Water quality enters the following production functions:

- Food (agriculture) – through abstraction for irrigation
- Industrial and commercial production – raising water treatment and filtration costs
  - Reservoir, port and river authorities incur costs from sedimentation and dredging
  - The costs and productivity of downstream commercial and recreational fisheries are dependent on water quality
- Hydropower – sedimentation affects the operating costs of hydropower plants
- Drinking water – the operating costs of water companies are affected by water treatment for nutrient, pesticide and sediment concentration
- Transportation – siltation affects
- Housing – amenity values related to the quality of nearby waterways are incorporated into property values
- Physical health – water contamination leads to health impacts through the use of water for recreation and consumption
- Recreation – through the immersive use of water for recreation (e.g. swimming, windsurfing), the contact use of water for recreation (e.g. kayaking, boating, rafting) and the indirect use of water for recreation (aesthetic part of landscape)
- Artistic – as an input to or inspiration for the production of art by amateur and professional artists
- Learning – opportunities for educators, students and researchers to learn from and experience the environment
- Spiritual and cultural – for spiritual, ceremonial or celebratory purposes
- Non-use value – the benefits trees provide for people who care about existence value of the environment (those who think it is important to preserve the environment for moral/ethical connection or fear of unintended consequences) or bequest values (those who think it is important to preserve the environment for future generations).

Beneficiaries

Water companies, water bill payers, agricultural workers, fisheries, energy producers and recreational users are all potential beneficiaries from improvements in water quality.

Valuation methods

The majority of the surveyed valuation literature on woodlands and water quality either (i) uses cost-based methods to explore the impact of woodlands on the price of water or (ii) uses stated preference methods to estimate the recreational value of water quality improvements. However, specifically attributing increased recreational values to forest services is difficult, and remains understudied. The literature review revealed a variety of permutations of these approaches including cost-based methods using water bills; stated preference methods such as choice experiments; and contingent valuation. Recent studies have seen a resurgence of interest in using revealed preference methods for estimating recreation-related values.

Valuation scale

Studies have been conducted at both the local (e.g. river, basin, municipality, water supply system level) and national scale (for the UK, France and Ecuador).

In principle, valuations should be transferable across locations. However, attempts to transfer stated preference valuations of water quality have met with mixed success (Hanley, Wright and Alvarez-Farizo, 2006; Bateman, Brouwer *et al*., 2011; Ferrini, Schaafsma and Bateman, 2014). A key issue is the extent to which spatial context (i.e. the location of substitutes, population, transport infrastructure and so on) can be adequately incorporated into valuation functions and hence transferred.[6] In cases where such incorporation is poor (e.g. where information regarding the availability of substitutes is unavailable) then errors may be lower if relatively simple valuation functions (e.g. ignoring some contextual factors) are used for transfer purposes (Bateman, Brouwer *et al*., 2011). However, the increasing availability of highly detailed spatial data (Bateman, Day *et al*., 2014; Sen *et al*., 2014) raises the potential for transferring more detailed valuation functions, yielding more accurate estimates of value. In general the cost of analysis and the degree of accuracy required for robust decision-making should guide the choice of transfer approach.

[6] A related issue concerns the transferal of valuations across periods. There is a developing literature on this issue and while much of this concerns water quality (e.g. Brouwer and Bateman, 2005), to date little relates to woodland.

Valuation estimates

The Woodland Valuation Tool currently contains 18 valuation studies or reviews and 27 references to biophysical studies relating to water quality. This literature examines the value of water quality changes to a variety of beneficiaries and across multiple contexts, a summary of which is given below.

Water companies

Woodlands generate water quality improvements which in turn benefit water companies through reductions in the treatment costs associated with the production of drinking water. These potential gains are only realised if water companies are able to respond to improvements in water quality by altering water treatments. In areas where water quality is relatively good this could be achieved by reducing mixing (the volume of clean water added) or by reducing chemical cleaning. All, some portion or none of these benefits may be retained by the water company as profits, or passed on to consumers in the form of reduced water bills. In areas where quality is poor large investments (sunk costs) in technology (e.g. carbon filters) may have already been made which limit the cost savings that can be made, thus reducing the benefits to water companies.

Willis (2002) disaggregates water treatment costs into energy costs and expenditure on chemicals (Table 2.1). These costs are identified on the basis of personal communication with McMahon (2001), and applied uniformly across all companies in England and Wales (Willis, 2002). However, actual costs are likely to vary (possibly substantially) between companies and across regions due to differences in water treatment technologies, capacity and availability of substitute water sources. Moreover, per unit treatment costs may not be constant due to different sources and types of pollution.

Long-run marginal costs for water supply and water treatment costs were obtained by Willis (2002) and Willis *et al*. (2003) via OFWAT and direct communication with water companies. However, due to the confidential and preferential nature of water treatment and abstraction cost information, long-run marginal costs and water treatment costs are not publicly available and are scarcely reported in academic literature. It should be noted, however, that there are significant issues with this work; for example, effects were examined within 1 km squares but not across them, and as a result the values are likely to substantially underestimate the benefits. Furthermore, since the Willis (2002) values were obtained there have been a number of changes to the regulation of water companies, for example through the introduction of the future price limits system in 2011 and the 2014 pricing review.[7] The economic value of clean water should be invariant to these regulatory issues; however, since the values reported in Willis (2002) and Willis *et al*. (2003) are related to market costs they are not independent of such issues. In addition, water abstraction costs are strongly related to the flow of water at abstraction points. Flow rates, and indeed the location of abstraction points, are likely to have changed over the last decade, implying that the costs reported by Willis (2002) and Willis *et al*. (2003) are potentially unreliable and should be interpreted as imperfect estimates.

Water bill payers

Water quality improvements generated by trees benefit water bill payers by reducing treatment costs in the production of drinking water. All, some portion or none of these benefits may be retained by the water company as profits, or passed on to consumers in the form of reduced water rates.

The following list gives recent examples considering the value of water quality improvements to households through surveying the resident population or collecting data on their water bills:

- Fiquepron, Garcia and Stenger (2013) develop a cost-based econometric model to assess the benefits provided by forests in France in terms of improved water quality,

[7] https://www.ofwat.gov.uk/pricereview/pr14/

Table 2.1 Treatment costs per million litres treated (from Willis, 2002).

Cost expenditure category	Treatment cost per million litres treated by water companies
Power	GBP 25
Chemicals needed to treat water from 'good groundwater' sources	<GBP 1
Chemicals needed to treat water from groundwater sources that require enhanced treatment	~GBP 2
Chemicals needed to treat surface water sources	~GBP 15

estimating that on average 1 ha of afforestation would generate a saving for French domestic users of around EUR 22 per year for all domestic users (in 2004 euros).
- Abildtrup, Garcia and Stenger (2013) develop a spatial econometric analysis of the effect of forest land use on the cost of drinking water supply in Vosges, France, and found a reduction in household water bills of EUR 98.93–138.46 per hectare per year (in 2008 euros) of new forest.

These estimates reflect the benefit to water bill payers through reductions in the cost of clean water. However, it is feasible that cost savings are not fully passed on to customers and so there may also be benefits in terms of increased profits to water companies. Our review found no studies that attempt to calculate changes in profits and so it is possible that the published literature on changes to customers' bills does not capture the full monetary value of the impact of woodlands on water quality.

Agriculture and fisheries

While reductions in the quantity of water available clearly have the potential to impact negatively upon agricultural output, with respect to water quality the literature is dominated by studies examining the impact of farming upon quality as opposed to the effect that reduced quality may have upon farm output (Shalhevet, 1994). Internationally the impact of woodland loss upon water quality and thereon upon agriculture has been prominent in areas subject to saline intrusion. For example, in southeast Australia trees can protect topsoil by keeping saline aquifers sufficiently discharged thereby allowing crops to be cultivated. However, the felling of trees in such areas has allowed saline intrusion and the loss of arable produce (Walker *et al*., 2010). While examples such as the above provide useful guidance as to the valuation of water quality impacts upon production (see also Bateman, Mace *et al*., 2011), our review failed to find examples relevant to woodland-induced water quality effects upon UK agriculture.[8]

Riparian and floodplain woodland improves water quality by acting as a physical buffer preventing sediment, pesticide and nutrient runoff (Nisbet, Silgram *et al*., 2011); additionally, the shade produced by trees can help reduce water temperature and has been associated with increased oxygen levels benefitting aquatic life. An example from Oregon, USA, shows woodland planting being used to reduce water temperature. The waste water from a water treatment plant had the effect of increasing the temperature of the river to levels that subsequently negatively affected the salmon population. Rather than paying an estimated US$ 150 million on cooling technology the water treatment company instead paid farmers to plant trees along the river to increase levels of shade and therefore reduce the water temperature (Bienkowski, 2015). In the UK, riparian shade was found to have a substantial influence on water temperature; for certain species, such as the brown trout, water temperatures above a threshold amount can be lethal and riparian shade was found to be an effective way of moderating the extremes in temperature during the summer months (Broadmeadow *et al*., 2011).

Hydroelectric producers

The prevention of sediment runoff from the physical buffer created by riparian and floodplain woodland may also affect hydroelectric producers. The main cost to hydroelectric companies from sediment is likely to be a reduction in storage capacity from the build-up of sediment in the reservoirs; in addition, sediment is one of the factors which ultimately determines the lifespan of a reservoir (Halcrow Water, 2001). The management of sediment levels is a cost for hydroelectric companies through activities such as dredging and sediment flushing. Riparian trees may therefore reduce the running costs of such activities; however, our review failed to find examples relevant to the effect of woodland-induced sediment reductions upon UK hydroelectricity.

Recreational users

Tree-induced improvements in water quality benefit recreation users through enhanced enjoyment of outdoor activities, including swimming in lakes and rivers, boating and recreational fishing.

A number of studies relate UK water quality to values derived from recreation (Hanley, Wright and Alvarez-Farizo, 2006; Metcalfe *et al*., 2012; Sen *et al*., 2014) and related activities such as recreational fishing (Butler *et al*., 2009).[9]

[8] Willis (2002) argues that, because of subsidies, the marginal social cost of agricultural production exceeds its marginal value to society, so the cost of reduced water quality is likely to be low at the margin. However, water quality problems may well not be confined to marginal farms. A separate argument may be that the lack of literature in the UK context is symptomatic of this being a minor issue. While gaps in the literature should not generally be interpreted as indicators of low values, in this case it may be true.

[9] In an extensive meta-analysis of water quality values in the USA, Van Houtven, Powers and Pattanayak (2007) map water quality changes from 90 studies onto a 10-point water quality index (WQI), where for instance a score of 2.5/10 referred to 'boatable', 5.1 referred to 'fishable' and 7.0 was 'swimmable'. They found the average value per unit of a change in water quality (on their composite WQI) ranged from US$ 2.6 to US$ 155, with a mean of US$ 30.6 (in 2000 US$). A more recent meta-analysis of the value of forest conservation for water quality protection in the USA (Kreye, Adams and Escobedo, 2014) found several important drivers of willingness to pay for water quality: type of conservation instrument (tool), aquatic resource type, geographic context, spatial scale, time and household income. The values provided in Kreye,

A variety of approaches have been used to estimate values including revealed and stated preference methods (e.g. Bateman, Abson *et al*., 2011). Both methods tend to yield values for the amalgam of attributes that constitute water quality as perceived by visitors and it may be difficult for the analyst to identify the relative weights placed on specific attributes. For example, while changes in clarity might be clearly perceived, other issues such as aquatic biodiversity, impact on health and pollutant concentrations might be progressively more difficult to disentangle (although a given project appraisal may not require such fine distinctions in order to assess a given investment option).

Values have been found to be responsive not only to changes in quality but also a variety of factors including socio-economic variables (e.g. income), the use of the resource by the individual, geographical region, programme scale, type of water body and the specific conservation tool proposed (Kreye, Adams and Escobedo, 2014). Incorporating many of these variables in a recent UK-based study, Sen *et al*. (2014) use the MENE database (Natural England, 2010) of over 40 000 household surveys to predict recreation visit numbers to different types of natural resource across Great Britain (see Section 5). This is combined with a new meta-analysis of the recreational value literature which estimated an average value of GBP 3.34 per person per visit to woodlands and forests and a value of GBP 1.82 per person per visit to freshwater and floodplains. However, the contribution of woodland to water quality and its role in supporting recreational values was not disentangled.

Research gaps

Relatively few studies focus on water companies, hydroelectric power generators and industry as beneficiaries of the water quality improvements generated by forests and woodlands. The relative lack of robust cost information makes this a priority area for future research. For instance, Willis (2002) resorts to using water treatment costs derived on the basis of a personal communication (reflected in Table 2.1). This cost information underpinned Willis *et al*. (2003) and Eftec (2011), but it is not clear that these costs are necessarily representative across England and Wales.

Expanding and formalising the evidence base in this area is a necessary first step towards a deeper understanding of the potential impact of forestry induced water quality changes on water companies.

- There is a need to extend the valuation of different pollutants and their removal from waterways. This needs to be flexible in terms of the scale of analyses, embracing both catchment and national levels. For example, there is a gap in the literature with respect to explicit valuation of sediment impacts, acidity and turbidity in the UK, although various studies appraise the overall benefits of woodland-related water quality changes.
- Many valuation studies fail to link water quality outcomes to woodland management or planting actions. This makes it difficult to establish causality and limits the usefulness of these valuation studies for making investment decisions when the objective is to achieve specific improvements in water quality.
- Most of the literature concerning trees and water quality focuses upon the impacts of new afforestation programmes rather than changes in management applied to existing woodlands (as an example of the latter see the study of preventing deforestation by Kreye, Adams and Escobedo, 2014).
- Reliable, representative data on treatment costs faced by water companies across Great Britain are essential to understanding the benefits of water quality improvements. This would require detailed treatment cost data, information on upstream land use and catchment management (spatial configuration of forested areas) and sedimentation rates.
- Once valuation functions linking woodland to water quality are established there remains a literature gap in terms of determining the most appropriate approach to transferring results across locations and time periods.

[9] *Continued from page 20:*
Adams and Escobedo (2014) and Van Houtven, Powers and Pattanayak (2007) focus exclusively on willingness to pay generated through stated preference studies. While this may simplify the process of conducting meta-analyses, it excludes all revealed preference and cost-based techniques which may hold greater validity for a range of final environmental goods and services and beneficiary combinations. Incorporating many of the key variables identified in these studies, Sen *et al*. (2014) value recreational visits to freshwater and floodplain ecosystems in the UK, reporting an average value of GBP 1.82 per person per trip.

Water availability and flood alleviation

Biophysical evidence	Valuation evidence	Decision support tools	Urban tree literature
Data are needed to validate models, (e.g. at catchment scale). Robust biophysical evidence quantifying the relationship between local woodland management, location and forest design, and changes in the quantity of water available is needed to support reliable valuation and decision-making. The impact of climate change and rising CO_2 levels on the water use of trees needs to be examined as this will affect the services (dis-services) provided in the future.	Key business interests such as manufacturing and industrial production, agriculture and the energy sector are all potential beneficiaries for whom values associated with water quantity are not robustly known.	There is a clear need to integrate the variety of values associated with water resources and the role that woodlands can play in enhancing these.	i-Tree Eco includes a module which uses hydrological models developed for the USA to compute the quantity of storm water capture. The value of avoided runoff is based on estimated or user-defined local values. As the local values include the cost of treating the water as part of a combined sewage system the lower, national average externality value for the USA is utilised and converted to local currency with user-defined exchange rates.

Key: Strong evidence · Good evidence but some gaps · Major gaps in evidence

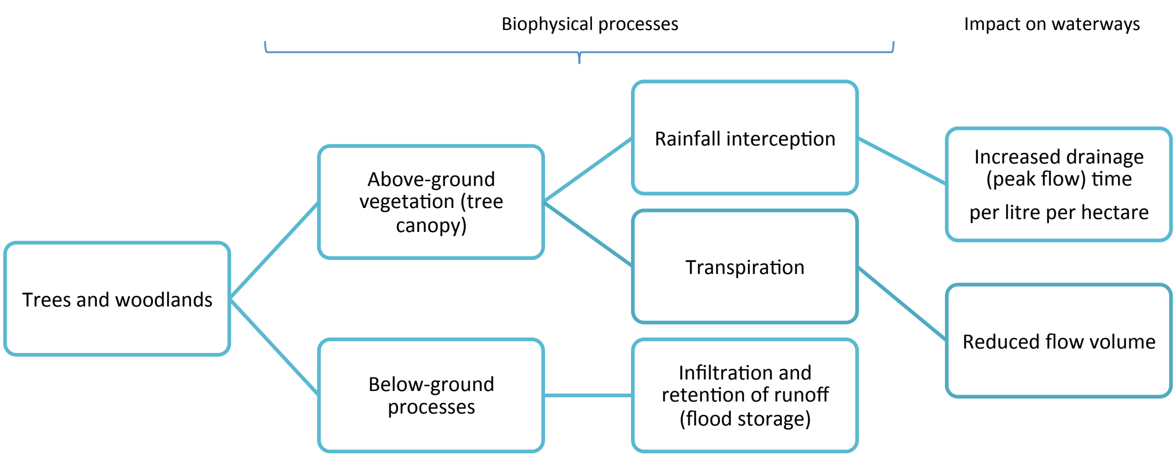
Biophysical pathways

Trees and woodlands impact on water quantity through a number of pathways, although the effect varies substantially over space and for different species of trees; for example the benefits vary depending on whether the area is wet or dry, while conifers use more water than broadleaf species. The key pathways are illustrated in Figure 2.2.

Examples of these biophysical pathways include:

- As above-ground vegetation trees and woodlands increase surface roughness, which reduces the overland flow of water and they are known to use more water than many alternative land uses (e.g. grass); the tree canopy intercepts rainfall and trees have low water losses through transpiration (Calder *et al*., 2008). As a result, well-positioned trees and woodlands can help to reduce surface water flow volume and the time taken for one litre of rainwater to be drained through 1 ha of land during peak flooding events (peak flow time). The impact of trees and woodlands on water availability depends on woodland type, tree species and location. In some circumstances planting woodland can increase water availability, for example planting broadleaved woodland on chalk (Roberts, Rosier and Smith, 2005). The planting of trees also affects precipitation through evapotranspiration; to fully understand the effect of afforestation or deforestation requires an understanding of the full hydrological cycle, and as a consequence the overall role of forests on the supply of water quantity is still an open

Figure 2.2 Biophysical processes of woodland influencing water quantity.



- empirical question. The absence of robust biophysical evidence to quantify the relationship between woodland and changes in the quantity of water available constitutes a significant barrier to reliable valuation and decision-making. (Ellison, Futter and Bishop, 2012).
- Below ground tree root networks increase the retention of water in soils through the 'sponge effect' (Thomas and Nisbet, 2007; Calder *et al*., 2008; Armson, Stringer and Ennos, 2013). Again, as a result, well-positioned trees and woodlands can help to reduce flow volume and increase peak flow times.

Recent flooding in the UK coupled with predicted increases in the number of flood events due to climate change has stimulated an interest in the potential for woodlands as a source of flood prevention and alleviation (Nisbet, Marrington *et al*., 2011; Nisbet *et al*., 2015). However, the results of studies that have attempted to quantify this potential have been varied (Van Dijk *et al*., 2009), and this has led some forest hydrologists to argue that woodlands have a limited impact on flood prevention, while others argue that there is an impact. The degree of effect declines with prolonged and heavy rainfall[10] and depends on many factors, such as scale, location, type and management of woodland. Process understanding suggests that woodlands have a role to play, which can be demonstrated in modelling studies but so far to a limited degree in terms of observed data at the catchment level.

However, there is evidence to support the hypothesis that woodlands can provide flood alleviation through reducing runoff and slowing flood peak travel times (i.e. delaying the arrival of floodwater at entrances to waterways). Armson, Stringer and Ennos (2013) found that trees reduced runoff by up to 62% in comparison to asphalt. However, this comparison might not be universally applicable as the alternative land use may not always be asphalt. In addition to alternative land uses the spatial configuration of trees has been shown to be important in determining the flood reduction services they provide. For example, Thomas and Nisbet (2007) developed simulation models to show that the spatial configuration of trees had substantial impacts on the depth of floodwater within woodlands, the flood storage volume upstream, velocity of water flow across the floodplain and the timing of the flood peak.

Final environmental good or service

The final environmental goods or services are woodland-induced changes in the quantity of water, particularly in surface waters. These goods and services are presented in the 'impact on waterways' section of the biophysical pathways in Figure 2.2. Benefits include flood alleviation, flood prevention and water storage (Calder *et al*., 2007; Nisbet, Silgram *et al*., 2011). Costs include the potential to limit water availability for direct abstractors, including water companies, and the agricultural, industrial and manufacturing sectors.

Water availability units

Flow speed (m s^{-1}), volume (m^3), number of properties affected or protected and the degree and value (GBP) of impact.

Economic production functions

Water quantity enters the following production functions:

- Food – availability of water for agriculture (including rain-fed systems and abstraction of water for irrigation) and reduced flooding of land
- Industrial and energy production – abstraction of water for production, cleaning and cooling (coal and nuclear power) and reduced flooding of infrastructure and buildings
- Hydropower – use of water for the direct generation of power
- Drinking water – potable supplies for domestic consumption
- Transportation – siltation effects
- Flood alleviation – volume and timing of flood flows
- Housing – amenity values related to the quality of nearby waterways are incorporated into property values
- Recreation – through the direct use of water for recreation (e.g. swimming, windsurfing, kayaking, boating, rafting) and indirect use for waterside for recreation
- Views– as a part of the landscape
- Artistic – as an input to or inspiration for the production of art by amateur and professional artists
- Learning – opportunities for educators, students and researchers to learn from and experience the environment
- Spiritual and cultural – for spiritual, ceremonial or celebratory purposes
- Non-use value – the benefits trees provide for people who care about existence value of the environment (those who think it is important to preserve the environment for moral/ethical connection or fear of unintended consequences) or bequest values (those who think it is important to preserve the environment for future generations)

Beneficiaries

Water companies, water bill payers, residential property owners, industrial producers, energy producers,

[10] In these cases the woodland canopy will reach a threshold in terms of the quantity of water that it is able to intercept, and thus the soil beneath the canopy is likely to become fully rewetted despite some rainfall being intercepted (Calder *et al*., 2008).

manufacturers and farmers are all beneficiaries of water availability and flood alleviation.

Valuation methods

Where studies on changes in water quantity attributed to woodland exist, the majority use cost-based methods to either estimate the cost savings to the water bill payer through avoided costs (associated with treating water by mixing in quantities of clean water) or estimate the avoided flood damage to properties. Such methods fail to measure the full economic value of these benefits. For example, in the case of flooding, the market price of repairing flood damage (i.e. its avoided cost) ignores the wider psychological and trauma effects of experiencing a flood. These are captured in the full economic cost of a flood (or the benefits of its avoidance), which are reflected in an individual's willingness to pay.[11]

Methodological advances are still required to enable the biophysical modelling to make robust (e.g. validated, repeatable and scalable) predictions of changes in water quantity attributed to woodlands. Projects such as 'Slowing the flow at Pickering' (Nisbet *et al*., 2015) provide a useful initiative for extending the knowledge base, but a robust understanding of the relationship between changes in woodland planting and management and their consequences for water availability and flooding remain a research gap.

Valuation scale

The majority of evidence reviewed assesses the effect upon water quantity of small stands at local region or city level. Extrapolating these findings becomes difficult as the scale increases. Indeed, Calder *et al*. (2008) comment that extending findings to a large catchment scale requires an understanding of a range of complex, interacting factors such as the diversity of the woodland structure and species; land-management practices; location of precipitation; runoff pathways; the topography; geology and soil structure.

Valuation estimates

The Woodland Valuation Tool currently contains 12 valuation studies or reviews and 14 references to biophysical studies relating to water quantity. These concern values to a number of beneficiaries as follows.

Water companies

Changes in water availability due to trees could affect water companies if increased scarcity impacts water abstraction costs for the production of drinking water. Willis (2002) uses hydrological models to assess the impacts of lower water availability upon water companies, noting that greater water scarcity may increase abstraction costs. Increased scarcity can affect short-run costs if companies have to expend greater effort (e.g. energy costs) abstracting from existing sources, and long-run costs if they need to move the location or expand the number of abstraction points.[12]

Willis (2002) and Willis *et al*. (2003) argue that across most of England and Wales there is sufficient water availability to meet demand from both forests and water companies and thus forest-induced reductions in water availability impose zero costs on water companies. However, due to the spatial heterogeneity in water availability, weather patterns and demand (from humans and forestry) for water across the UK, there are areas and times of year during which water scarcity imposes costs on water companies. Aggregating information on water availability and forest water demand to the county level, Willis (2002) estimates that the externality costs range between GBP 0.13[13] (in Cleveland) and GBP 1.24[14] (in Dorset) per m^3 of water abstracted[15] with a mean of GBP 0.50[16] per m^3. Willis (2002) notes that these are upper bound costs for each county, and report a present value of the aggregate externality cost[17] to water companies of GBP 52.5 million for England and GBP 35.4 million for Wales, with an annual externality cost of GBP 5.3 million. These net costs incorporate both the negative externality (in terms of reduced water quantity) and a positive externality (in terms of improved water quality and hence lower treatment costs within abstracted waters).

For urban trees, Rogers, Jaluzot and Neilan (2012) estimate the value of the avoided water runoff by calculating the energy saved from water companies not having to treat that water in addition to the carbon value of that energy saving. In the Victoria Business District, London, the value of avoided surface water runoff is estimated at GBP 29 000

[11] The difference between the customer's willingness to pay and the cost price of a good is known as the consumer surplus.

[12] This latter option may in turn alter the costs of treating water for quality purposes. For example, if water companies are forced to react to lower availability of water by abstracting within poorer quality watersheds then this might increase treatment costs.
[13] This and all values in this paragraph are reported in 2001 GBP.
[14] Eftec (2011) rounds these to GBP 0.10–GBP 1.25.
[15] This only refers to water abstracted by water companies across England and Wales.
[16] Calculated by CSERGE in 2015 based on Willis (2002) Tables 1 and 2.
[17] Calculated using a 25-year time horizon and using the then Treasury discount rate of 6%. Note that Willis *et al*. (2003) state that they assume 'a direct one-to-one trade-off between forestry and water availability' (p. 26). It is presumed that this is an assumption that a 1 m^3 uptake of water by forests translated directly to a 1 m^3 reduction in water availability for abstraction. Note also that Willis *et al*. (2003) could not calculate an externality value for Scotland due to a lack of data on water supply costs.

per year in energy savings and nearly GBP 21 000 per year in carbon savings. These estimates reflect either an increase in profits for the water company or savings to water bill payers through reductions in the cost of clean water depending on whether these savings are passed on to the customers.

Water bill payers

Reduced water availability due to trees could affect water bill payers if increased scarcity affects drinking water costs that are passed on from water companies to bill payers. However, water bill payers may also benefit from avoided surface water runoff leading to reduced sewerage charges.

A number of UK studies have valued the ecosystem services provided by urban trees. Two of those studies include a valuation for avoided surface water runoff. Avoided sewerage charges have been estimated at GBP 1.1 million per year in Glasgow (Rumble *et al*., 2015) and GBP 0.46 million per year in Wrexham (Rumble *et al*., 2014). To calculate these figures the authors first estimate the total amount of water interception attributed to urban trees using an i-Tree Eco survey (see discussion in Section 10) and then multiply this by the rate charged by the local water company for sewerage.

On a larger scale or in non-urban areas there are very few studies; one exception is from Chile in which Núñez, Nahuelhual and Oyarzún (2006) model a change in forest cover from native to plantation forest which they claim would result in a reduction in the quantity of water available for abstraction. The authors value the change in water available using the average unit cost of water over the study period. The authors report a mean value of US$ 86.5 per hectare of native forest per year in 2004 US$.[18] Our review found no large-scale studies in the UK which attempt to value tree-induced changes in water quantity for water bill payers.

Residential property owners

Flood regulating services generated by trees benefit residential property owners by reducing the likelihood and intensity of flood events.

To establish if changes in land use and land management can help reduce flood risk a modelling, monitoring and evaluation programme was set up in 2009 by Defra, known as 'Slowing the flow at Pickering' (Nisbet, Marrington *et al*., 2011). Since Phase I of the study has previously been documented in Eftec (2011), we instead focus our attention on the recently published final report for the extension of the project (phase II) (Nisbet *et al*., 2015).

The specific land-management changes in the Pickering catchment included new planting of farm and riparian woodland; changes to existing forests and management including some small-scale felling and restoration; construction of large flood storage bunds and small timber bunds; and the construction of large woody debris dams. In total the programme has created 19 ha of riparian forest and nearly 15 ha of farmland forests.

The authors conducted an economic analysis of seven ecosystem services including flood regulation, the value of which was calculated as the avoided damage savings over a 100-year period (from the avoidance of flood damage to properties). For the riparian woodland planting and creation of 129 large woody debris dams in the Pickering Beck catchment the estimated avoided damage savings over 100 years are between GBP 55 000 and GBP 1 100 000 (in 2015 GBP based on a range of values (provided by personal communication with Dean Hamblin, Environment Agency) for annual savings per cubic metre of flood storage and discounted over the 100 years at the Treasury Green Book rate of 3.5%).

Industrial producers, energy producers and manufacturers

Direct abstraction of water benefits a number of different sectors of the economy as an input into cooling systems and waste dilution. Reduced water availability due to trees could affect direct abstractors if increased scarcity impacts water abstraction costs.

In 2011, 58.1% of water abstracted in England and Wales was for public water supply with the remaining 41.9% directly abstracted by various sectors of the economy (Office for National Statistics, 2015a). The energy production sector abstracted the largest proportion (over half of all direct abstraction including hydropower), and in addition the agricultural, forestry, fishing and manufacturing sectors also abstracted significant amounts. Byers, Hall and Amezaga (2014) and Byers *et al*. (2015) investigate potential future changes to water use with regard to electricity generation across the UK.[19] They use regional demand and supply of freshwater with respect to climate change projections and a range of decarbonising pathways. In general demand for

[18] The average is calculated by CSERGE (2015) from the summer value of US$ 162.4 and rest of the year value of US$ 61.2 per hectare reported in Núñez, Nahuelhual and Oyarzún (2006).

[19] Thermal power stations abstract water to use for cooling; in the UK, thermal power stations are responsible for approximately 5% of the UK's freshwater use.

freshwater abstraction for cooling is predicted to decrease; however, this pattern could be reversed in a future with a large uptake of carbon capture and storage (CCS) technology. The location of new power plants is also important; for example, by shifting power generation to estuaries or coastal environments the freshwater demand can be reduced. Under certain scenarios (e.g. high levels of new CCS) and assumptions (new capacity located inland) the Byers *et al*. (2015) models predict that certain regions will face water scarcity in which future demand exceeds future supply, and the reduced water availability due to trees could exacerbate this problem and cause increased costs for the direct abstractors of freshwater.

Farmers

Farmers benefit from water quantity as an input to rain-fed and manual irrigation systems, which are used to increase crop yields.[20]

To quantify the effects that woodland has on water flow in a catchment, detailed modelling is required. The exact positioning of the woodland in the landscape determines how much water is intercepted; soil type determines the storage of water in soils; and in addition other variables such as topography, geology and climate are also important.

As with water companies and other direct abstractors of water there may be costs to farmers from a reduction in water available for abstraction (Kijne, Barker and Molden, 2003); however, the higher interception and retention of wooded landscapes compared to other land uses may reduce problems with flooding (Nisbet, Marrington *et al*., 2011). The costs and benefits to farmers are likely to be highly specific to the precise location and time, and therefore it is difficult to say whether the net effect of trees is positive or negative for farmers. The higher interception rate of wooded landscapes may reduce the available water for direct abstraction, at the same time forest and woodland soils have been shown to store more water than other land-use types (Bird *et al*., 2003) potentially increasing the soil moisture of agricultural land close to woodlands as well as reducing the risk of flooding. The potential for modelling this relationship between woodlands and water quantity was outlined as part of ADAS and Eftec (2014) for the UK.

Research gaps

- There is a clear need to integrate the variety of values associated with water resources and the role that woodlands can play in enhancing these.
- There exists a variety of evidence on the biophysical relationships between tree cover and water quantity (e.g. through modelling studies and to a much lesser degree through observed data at the catchment level). To fully quantify the effect of afforestation or deforestation data are needed to validate models, especially at the catchment scale. The absence of robust biophysical evidence quantifying the relationship between local woodland management, location and forest design, and changes in the quantity of water available constitutes a significant barrier to reliable valuation and decision-making, particularly as scale increases. There is also a gap in the evidence base in terms of the impact of climate change and rising CO_2 levels on the water use of trees, which will affect the services (dis-services) provided in the future.
- The current literature linking trees and woodlands to the prevention of flooding is growing; however, a wide variety of other factors are involved in flood events. A full economic valuation would need to take into account the availability of substitutes, the effect of trees and woodlands on the timing and severity of flood events and catchment level impacts in order to fully quantify the effect of upstream tree planting or woodland management changes on the probability of downstream flooding.
- Evidence on the economic valuation of changes in water quantity associated with woodlands is lacking for a variety of beneficiaries. Key business interests such as manufacturing and industrial production, agriculture and the energy sector are all potential beneficiaries for whom values are not robustly known.

[20] This is particularly relevant for potato farming, the most intensively irrigated crop in the UK (MacKerron, 1993).

3. Air quality

Biophysical evidence	Valuation evidence	Decision support tools	Urban tree literature
The biophysical pathways through which trees affect air quality are relatively well understood for both rural and urban trees, although debate remains regarding the efficacy of urban forests for improving air quality through pollutant deposition and absorption.	The health impacts caused by air pollution depend upon the number of people being exposed: a tonne of SO_2 in a densely populated area causes more damage than a tonne in a sparsely populated area. The value of pollution absorption by trees should reflect this population exposure.	Although i-Tree and integrated analyses such as the UK NEAFO's TIM provide some assistance, decision support tools which account for the spatially varying impact of air quality improvements are needed.	i-Tree Eco computes the value of removal of air pollutants (NO_2 PM_{10} and SO_2) using a constant value per tonne based on social damage costs for the UK.

Key: Strong evidence; Good evidence but some gaps; Major gaps in evidence

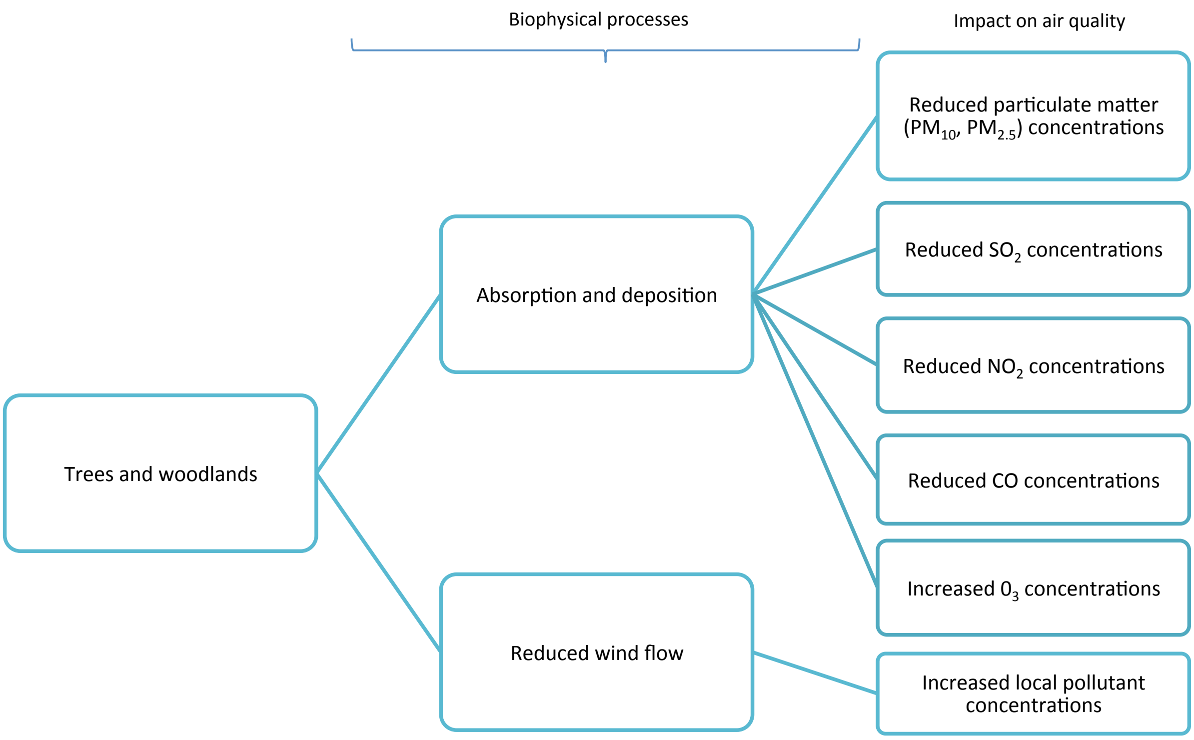
Biophysical pathways

Trees and woodlands impact on air quality through a number of pathways, as illustrated in Figure 3.1.

Trees can act as biological air filters; their large leaf area relative to their ground footprint and the absorption properties of their surfaces enable them to remove certain airborne particles and improve the air quality of polluted environments through absorption and deposition (Beckett, Freer-Smith and Taylor, 1998, 2000):

- Urban tree planting can reduce PM_{10} (particles smaller than 10 μm) concentrations (Bealey *et al*., 2007). The World Health Organization notes that the primary health effects of PM_{10} include damage to the respiratory and cardiovascular systems. Due to the small size of PM_{10}, they can penetrate the deepest parts of the lungs. McDonald *et al*. (2007) predict that increasing the total tree cover in the West Midlands from 3.7% to 16.5% could reduce PM_{10} concentrations in the West Midlands by 10%, removing 110 tonnes per year of primary PM_{10} from the atmosphere.
- Tallis *et al*. (2011) provide evidence from the Urban Forest Effects Model to support the hypothesis that targeted

Figure 3.1 Biophysical pathways of woodland influencing air quality.



planting of broadleaved trees to expand the urban canopy of the Greater London Authority would provide a large benefit to future air quality through the removal of 1109–2379 tonnes of PM_{10} from the urban boundary layer. In particular, targeting of street tree planting in the most polluted areas would have the greatest benefit to future air quality. The increased deposition would be greatest if a larger proportion of coniferous to broadleaved trees were used.
- The potential air quality improvements provided by each tree depends on the species and maturity of the tree. Donovan *et al*. (2005) quantified this using a series of model scenarios to develop an urban tree air quality score; they considered 30 species and found that pine, larch and silver birch have the greatest potential to improve urban air quality, while oaks, willows and poplars can worsen downwind air quality if planted in very large numbers.

However, it should be noted that significant debate remains regarding the efficacy of urban forests for improving air quality through pollutant deposition and absorption. Furthermore, there are also pathways through which trees have been found to reduce air quality. For example, Vos *et al*. (2013) note that urban trees can reduce wind flow, thereby preventing dilution and creating increased local pollutant concentrations. Other potential localised air quality problems associated with trees include the production of allergens such as tree pollen and the release of volatile organic compounds that can increase ozone (O_3) concentrations (Owen *et al*., 2003; McDonald *et al*., 2007).

Final environmental good or service

The final environmental goods are changes in air quality attributed to woodlands.

Air quality units

The existing literature considers the effects of trees upon concentrations of a number of major air pollutants, including CO, NO_2, O_3, PM_{10}, $PM_{2.5}$ and SO_2. Not all studies incorporate all of these pollutants. Studies that apply monetary estimates to reductions in these pollutants typically refer to the mass (kg, tonnes) absorbed by trees over a particular period of time (usually annual). Some studies provide monetary estimates in terms of reduced mortality and morbidity (often referring to delayed deaths and avoided hospital stays due to respiratory illness).

Economic production functions

Air quality enters a number of production functions:

- Agriculture – air pollution can affect crop yields and quality
- Housing – residential properties located in areas of poor air quality (e.g. those exposed to emissions from road traffic) have lower property prices (Bateman *et al*., 2001)
- Physical health – air pollution is associated with respiratory illnesses/diseases, hospital visits and early deaths (Powe and Willis, 2002, 2004)
- Mental health – the impact on mental health, for example through stress and anxiety caused by exposure to air pollution
- Recreation – air quality at recreational sites could alter the benefit derived from a trip, for example through reducing the aesthetic value of the site or by exposing recreational visitors to increased health risks
- Learning – opportunities for educators, students and researchers to learn from and experience the clean air. Exposure to air pollution has also been shown to affect the educational attainment and attendance of children (Gilliland *et al*., 2001; Mohai *et al*., 2011; Miller and Vela, 2013)
- Spiritual and cultural – by altering the value derived from the use of sites for spiritual, ceremonial or celebratory purposes
- Non-use value – the benefits trees provide for people who care about existence value of the clean air in the environment (those who think it is important to protect air quality for moral/ethical connection or fear of unintended consequences) or bequest values (those who think it is important to preserve good air quality for future generations)

Beneficiaries

Beneficiaries of improved air quality include all those affected by air pollutants. Those in urban areas may be most affected by improvements but rural populations may also benefit along with those visiting recreational resources. Residential property owners may also benefit where improved air quality increases property values. The localised dose–response nature of the impact of changes in air quality on health means that benefits accrue to people with respect to their individual level of exposure; accruing to those who live in the locality, those who visit for work or leisure, and those who pass through the area on a regular basis. It is important to note that most of the research reviewed focuses on highly localised (1 km^2) benefits from tree-induced air quality improvements. Further study is needed to determine impacts on a larger spatial scale.

Valuation methods

There are several potential methods for deriving monetary estimates of the benefits of improved air quality due to trees and forests. Two methods are commonly utilised: the first attempts to estimate a value for a marginal tonne of a pollutant and multiply that value by the change in pollutant; the second attempts to model the dose–response relationship between air quality and health impacts. The first method is employed in the US Forest Service's i-Tree Eco tool for valuing trees and forests, in that per unit values for pollution reduction (e.g. GBP per tonne of PM_{10}, $PM_{2.5}$, NO_2) are multiplied by the volume of pollutant reductions by trees and forests. There are however a number of issues which should be considered when using a constant value of pollutant method: (i) it is important to define what benefits or costs are considered in calculating the constant value and how they have been valued; (ii) the value of a marginal tonne may depend upon the baseline pollution concentration (so for example a unit of pollution in a low pollution area might have a lesser effect than an additional unit which pushes concentrations over some toxicity threshold); and (iii) the health effects of the pollutants are clearly related to the number of people exposed (so for example a tonne of SO_2 in a densely populated area causes more damage than a tonne in a sparsely populated area), and a unit value which does not vary by population exposure is a substantial simplification. The second method is employed in Powe and Willis (2002), in that the dose–response relationship between air quality improvements and reduced mortality and morbidity is modelled. By applying pre-determined monetary values for these effects the value of air quality changes can be estimated. Again there are a number of issues which should be considered when using this method, most notably how is the dose–response modelled and then how are those changes in mortality and morbidity valued? The physical and mental health part of this report (Section 6) covers these issues in more detail.

In addition to the above there are alternative options for valuing changes in air quality, such as the hedonic pricing methods that relate differences in house prices to differences in air quality or stated preference methods which attempt to estimate the general public's willingness to pay to avoid harmful pollutants.

Valuation scale

Most studies are highly localised, focusing on urban trees and woodlands. The i-Tree model, developed by the US Forest Service, has been applied from the level of individual trees to city-wide assessments (Hutchings, Lawrence and Brunt, 2012; Rumble *et al*., 2014, 2015). At a national scale, Powe and Willis (2002) assess air quality effects of trees at the 1 km^2 scale, focusing on woodlands of 2 ha or more. However, compared to other final environmental goods and services, relatively little research has valued the impact of trees and woodlands on air quality.

Valuation estimates

The Woodland Valuation Tool currently contains 14 valuation studies or reviews and 20 references to biophysical studies relating to air quality.

The economic value of woodland-induced air quality improvements is difficult to assess due to the long and complex chain of environmental and human production functions through which these improvements are generated and 'consumed'. Moreover, air quality is often implicitly included in broader ecosystem service valuation exercises. For instance, if part of the benefit people derive from urban woodland recreation sites is due to improved air quality, this may or may not implicitly be captured in a recreation valuation study, even if the study does not identify a value for air quality specifically. Similarly, an analysis of housing market prices may show a price premium for homes located near trees and woodlands, but may not specify the share of this premium that may be attributed to improved air quality versus recreation or visual benefits. A key issue in the use of such revealed preference valuation methods concerns the extent to which air quality benefits are perceived by individuals purchasing associated goods. So, in the case of (hedonic) property price studies, while a potential house purchaser may readily appreciate the visual amenity value of nearby trees, they may be unaware of the potential air quality benefits those trees may offer.

Given these challenges, there are two chief pathways through which the economic effects of woodland-induced air quality improvements have been identified and quantified: (i) estimate a constant unit value for a marginal tonne of a pollutant and multiply that value by the change in pollutant; (ii) model the dose–response relationship between air quality and those health impacts and multiply that by estimated values for a reduction in the risk of the health effects (mortality and morbidity).

- Hutchings, Lawrence and Brunt (2012) in Edinburgh, Rumble *et al*. (2014) in Wrexham, Rumble *et al*. (2015) in Glasgow and Rogers, Jaluzot and Neilan (2012) in London all applied Defra social damage costs[21] (a constant unit value for a tonne of pollutant) to estimate the value of pollutant removal by urban trees. Table 3.1 details the GBP per tonne social damage costs for three pollutants (NO_2, PM_{10} and SO_2) in 2010 prices.

All four studies (Edinburgh, Wrexham, Glasgow and London) utilise i-Tree Eco to estimate the reduction in these

[21] See Dickens *et al*. (2013) for guidance on valuing the UK's social damage costs on air quality.

Table 3.1 UK social damage costs (Dickens *et al.*, 2013).

Pollutant	UK social damage costs, GBP per tonne (2010 prices)
NO_2	955
PM_{10} transport (large)	70 351
PM_{10} transport (medium)	55 310
PM_{10} domestic	28 140
SO_2	1633

pollutants from trees located in the cities; these reductions are then multiplied by the per tonne UK social damage cost values to determine the value of the trees to air quality. The social damage values for the pollutants are derived using representative dispersion and exposure modelling and represent health impacts (morbidity and mortality) for all the pollutants. The PM_{10} and SO_2 estimates, in addition, include building soiling costs and the corrosive effect of SO_2 on building materials. For NO_2 and SO_2 a single fixed per tonne value is given, while for PM_{10} the damage cost depends on the location and the sector it is produced by (e.g. electricity supply, domestic, transport, agriculture). For urban environments the PM_{10} the most appropriate sector is likely to be domestic or transport. The three urban studies examined all use different PM_{10} values: Hutchings, Lawrence and Brunt (2012) in Edinburgh use the large urban transport value of GBP 70 351 per tonne; Rumble *et al*. (2014) in Wrexham use the medium urban transport value of GBP 55 310 per tonne; Rumble *et al*. (2015) in Glasgow use the domestic value of GBP 28 140 per tonne; and Rogers, Jaluzot and Neilan (2012) use UK social damage costs of GBP 273 193 per tonne of PM_{10} for inner London and GBP 178 447 per tonne of PM_{10} for outer London. It is important to note that these figures do not fully coincide with the definition of economic value set out in Section 1. These fixed values per tonne do not reflect marginal changes and therefore assume that the value of a unit of pollution reduction is entirely independent of the initial concentration. Furthermore, in the case of NO_2 and SO_2 they do not reflect the size of the population exposed to the pollution change.

- Powe and Willis (2002, 2004) and Willis *et al*. (2003) adjust Department of Health estimates for the willingness to pay to reduce the risk of mortality and morbidity in motor vehicle accidents (the adjustment is in order to more accurately reflect the mortality and morbidity risk profile from air pollution). Powe and Willis (2002), Willis *et al*. (2003) and Eftec (2011) report estimates of about GBP 125 000 for each death avoided by one year due to PM_{10} and SO_2 absorbed by trees, and GBP 600 for an 11-day hospital stay avoided due to reduced respiratory illness (Willis *et al*., 2003).

Both of these strategies require strong natural scientific underpinnings to generate valid estimates of pollution absorption by urban trees. Changes in estimates of the absorption rates of trees for specific pollutants will of course be reflected in corresponding estimates of the value generated. Table 3.2 illustrates this point by contrasting two valuations of the air pollution value of trees, which adopt differing estimates of absorption rates. As can be seen the chief feature of these results is the order of magnitude difference in estimated SO_2 absorption between the two studies. This in turn leads to order of magnitude differences in mortality and morbidity impacts, as well as on the upper and lower bounds of monetary benefits. This emphasises the sensitivity of valuation to the underpinning natural science evidence base. Reported absorption in the earlier study (Powe and Willis, 2002) is relatively high at 1.2 million tonnes of SO_2 absorption per annum. According to Defra statistics (Defra, 2014), and the National Atmospheric Emissions Inventory, UK SO_2 emissions in 2002 totalled about 1.0 million tonnes. Thus, Willis *et al*. (2003) and Eftec (2011) may overstate air quality values as they are based on an analysis that suggests trees in Great Britain extract more than 100% of Britain's annual SO_2 emissions. Using the later study (Powe and Willis, 2004) may offer a more conservative estimate.

Table 3.2 Sensitivity of air quality impacts to natural science evidence: annual estimates in GBP 2002.

Rainfall	Source	PM_{10} ('000 kg)	SO_2 ('000 kg)	Deaths brought forward	Hospital admission numbers	Total benefits ('000 GBP)	
						Lower bound	Upper bound
Days with >1 mm rain excluded	Powe and Willis (2002)	391 664	711 158	65	45	222	8198
	Powe and Willis (2004)	385 695	7715	5	4	17	629
Days with >1 mm rain included	Powe and Willis (2002)	617 790	1199 840	89	62	305	11 213
	Powe and Willis (2004)	596 917	11 216	7	6	25	901

The disparity suggests that clarifying SO_2 absorption rates by urban trees is an important area for research.

Note also that the Powe and Willis (2002, 2004) and Willis *et al*. (2003) studies all confine their focus to PM_{10} and SO_2 concentrations only, omitting effects on levels of $PM_{2.5}$, NO_2, CO and O_3. A more complete analysis of the air quality benefits generated by trees and woodlands should incorporate these additional pollutants.

Research gaps

There are several areas in which estimates of the value of improved air quality due to trees and forests could be enriched:

- Improving the natural science understanding of pollutant absorption and deposition in urban forests.
- Consideration of the wider remit of air pollution impacts in assessing the benefits of tree-related reductions of pollution should include health benefits both directly (in terms of the avoidance of morbidity and mortality impacts) and indirectly (e.g. by generating greater potential for beneficial outdoor activity and exercise). Also the effects of reducing air pollution on avoided damage to infrastructure such as building material damage and reductions in agricultural losses should be included.
- Moving away from a reliance upon unit values towards an approach which relates values to both the change in pollution levels and the baseline concentrations to which they are added would allow for non-constant marginal effects of pollution and reflect the changing conditions across locations.
- Allow for the fact that the health impacts of air pollution depend upon the number of people being exposed. A tonne of SO_2 in a densely populated area causes more damage than a tonne in a sparsely populated area. The value of pollution absorption by trees should reflect this population exposure.

4. Climate

Biophysical evidence	Valuation evidence	Decision support tools	Urban tree literature
The impact of climate change on the growth and biophysical functioning of trees (e.g. water use) needs to be examined as this will affect the services (dis-services) provided in the future.	Improving estimates of the social cost of carbon/abatement costs (carbon price is an active area of research, but is unlikely to be resolved in the short or medium term). Employing UK Government carbon prices is a straightforward compromise.	Decision-making tools which take account of the impact of climate on trees and woodlands, and the goods and services provided by them are needed.	The impact of trees on temperature regulation through shading has been incorporated into i-Tree Eco.

Key: Strong evidence — Good evidence but some gaps — Major gaps in evidence

Biophysical pathways

Trees and woodlands impact on climate through a number of pathways, as illustrated in Figure 4.1.

There are several pathways through which trees and forests affect climate, both locally and globally, and on both short and long-term time scales. The best understood relationship relates to greenhouse gas (GHG) flows, where GHGs, including CO_2, are exchanged between forest ecosystems, timber production and consumption and the environment through tree growth, decay and harvesting. The deleterious effect of GHGs on global climate stability means that GHG emissions have an economic cost, and sequestration services generate economic value. The full, discounted value of the net losses induced by emitting a unit of carbon today is known as the social cost of carbon. In addition to impacts on GHG flows, trees have short-term localised effects on climate, both directly (e.g. through the urban cooling effect of shade trees) and indirectly (if shade trees reduce carbon-intensive energy consumption by buildings). As discussed in Section 2, trees form an integral part of the water cycle and large-scale planting of trees can affect precipitation (Zhang *et al.*, 1997; Ellison, Futter and Bishop, 2012).

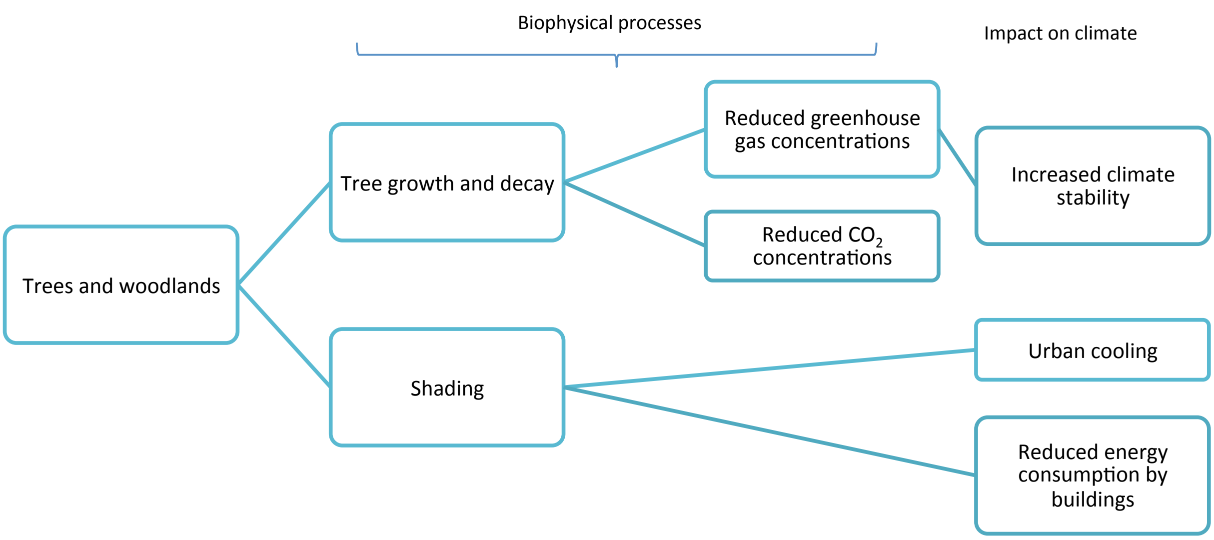
Final environmental good or service

The final environmental service is climate regulation attributed to woodlands.

Climate units

Common units for carbon flows include pounds per tonne of carbon (GBP t^{-1} C), pounds per tonne of carbon dioxide (GBP t^{-1} CO_2), pounds per tonne of carbon dioxide equivalent (this is useful for converting non-CO_2 GHGs into CO_2 equivalent units based on the degree of radiative forcing induced by various GHGs; GBP t^{-1} CO_2e). A common

Figure 4.1 Biophysical pathways of woodland influencing climate.



mistake is to confuse GBP t^{-1} C with GBP t^{-1} CO_2 (or CO_2e). These are not equivalent, as a tonne of C contains one tonne of carbon, whereas a tonne of CO_2 contains 0.2727 tonnes of carbon.

Common units for the benefits of urban shade trees include: temperature (degrees C or F); and units of energy saved (kW or kWh d^{-1}). Using information on relevant energy costs (which will vary according to time and location of the study) it is possible to link energy savings to monetary figures.

Economic production functions

Climate enters into a number of economic production functions:

- Food – through its effect on agricultural crop yields and livestock management
- Industrial production – through energy costs and requirements for cold storage
- Flood alleviation (amplification) – climate change has been linked to an increasing incidence of extreme events including flood events
- Housing – through energy costs and exposure to flood risk
- Physical health – through heat stress and exposure to extreme temperatures
- Recreation – climate change and associated weather conditions affect opportunities for recreational activities

Beneficiaries

Changes in climate affect the general public in both rural and urban areas, as well as residential property owners and energy bill payers.

Valuation methods

In a world of perfect information, cost-benefit analyses would use the social cost of carbon (SCC), defined as the cost of total global damages caused by an incremental unit of carbon emitted today, summed over its entire time in the atmosphere, and discounted to present value terms (Price, Thornton and Nelson, 2007). However, given the extent of uncertainty surrounding the precise impacts of climate change and their values, estimates of the SCC vary widely (Tol, 2013). Moreover, given the timescales involved, estimates of SCC are particularly sensitive to the discount rate used, as well as a multitude of other assumptions regarding consumption growth rates, projected CO_2 emissions, the carbon cycle, and environmental sensitivity to CO_2 concentrations and temperature change. Tol (2013) analyses 588 estimates of the SCC from 75 reviews, finding that the mean estimate is US$ 196 per tonne of carbon, while the mode is US$ 49 per tonne of carbon (for emissions in 2010, expressed in 2010 US$). This suggests that the average values are driven by a few very large estimates.

Given the wide range and inherent uncertainties surrounding the SCC (estimates span three orders of magnitude), there is justification for adopting alternative approaches. One such alternative entails setting an emissions cap or reductions target relative to some base level, and then estimating the cost of meeting it (Dietz and Fankhauser, 2010). Broadly, this is the marginal abatement cost (MAC) approach, where the MAC is the cost to polluters of reducing emissions by an incremental amount. Of course, significant uncertainties exist here as well, not the least of which entail the changing costs and efficacy of abatement technologies, but the uncertainties surrounding MAC estimates are narrower than those around the SCC, perhaps by as much as an order of magnitude (see Dietz and Fankhauser, 2010).

In 2009, the UK adopted a target consistent MAC approach to estimating carbon values for use in UK policy appraisal (DECC, 2009). Here, targets refer to artificial constraints on carbon emissions imposed by a regulatory authority (e.g. the UK Government, EU, UN or other international agreement), and are commonly expressed in terms of quantity of emissions (as in the EU Emissions Trading Scheme; EU ETS) or percentage reductions relative to some base year (as in the UK Climate Change Act 2008). In the UK context, there are separate carbon values for traded and non-traded sectors. This is justified by the fact that traded sectors are subject to the EU ETS, and thus face an implicit target determined by the cap on EU allowances, while the non-traded sectors fall outside the EU ETS and face targets set elsewhere, for example by the UK Government. These values are updated periodically, and the most recent revision is reported in Table 4.1.

The nature of carbon as a perfectly mixing pollutant means that the value of one tonne of carbon sequestered does not depend on the location of the sequestration. This allows the social cost of carbon to be applied with ease.

Valuation scale

Existing literature on the climate impacts of trees covers multiple spatial and temporal scales, ranging from monthly energy savings at individual houses (Akbari *et al*., 1997), to annual energy savings aggregated across major cities (Konopacki and Akbari, 2000; Nowak, 2010; Nowak *et al*., 2012), and finally to impacts on global GHG flows over extended periods of time (depending on the time to maturity, which varies by species).

Valuation estimates

The Woodland Valuation Tool currently contains 18 valuation studies or reviews and 10 references to biophysical studies relating to climate.

Unfortunately, there is no globally agreed value for carbon storage, and published estimates range from US$ -6.6 to US$ 2400 per tonne of carbon (US$ -24.2 t^{-1} CO_2 to US$ 52 800 t^{-1} CO_2), thus making comparisons across studies difficult (Tol, 2008). Identifying the appropriate value for a tonne of carbon storage remains a central challenge and is itself an active area of research (see Tol, 2011; Greenstone, Kopits and Wolverton, 2013; Nordhaus, 2014).

In response to the wide variation of SCC estimates, the UK Government now publishes a range of carbon values based on the abatement costs of meeting target emissions reductions for use in UK policy evaluation, with low, central and high estimates for both the traded and non-traded sectors (Table 4.1[22]). The distinction between traded and non-traded sectors is important as only the latter fall under the remit of the EU ETS). DECC guidance (DECC, 2009), assumes that these prices will converge (due to international policy developments) by 2030. The central estimate is expected to peak in 2077 at a value of GBP 341 t^{-1} CO_2e (in 2014 GBP) and fall thereafter. All values reported in Table 4.1 are in 2014 GBP per tonne of CO_2e, and therefore need to be multiplied by 44/12 in order to be compared with values reported per tonne of carbon.

Several approaches have been adopted when valuing the carbon benefits of trees and woodlands including (i) valuing annual carbon sequestration, (ii) valuing additional carbon sequestration provided by projects and (iii) calculating the net present value of carbon storage.

The annual value of carbon sequestration services is found by multiplying official UK values per tonne of carbon sequestration by the mass of carbon sequestered by trees each year. The UK carbon value per tonne assumes that the carbon is removed from the atmosphere permanently and is equivalent to the valuing of avoiding the release of one tonne of carbon into the atmosphere today. Permanence is a very important consideration in the valuation of carbon benefits; to be accurate the present value of the carbon at the point at which it is re-released to the atmosphere must be subtracted when valuing current gross sequestration.

However, as a simplification permanence issues can be ignored providing the total carbon stock in UK woodlands is expected to remain at least at the current level in perpetuity once carbon substitution benefits (associated with using wood instead of fossil fuels or more fossil fuel intensive materials) are also accounted for. This assumption is supported by the current upward trend in carbon stocks in UK woodlands and existing government targets to increase woodland (Valatin and Starling, 2010).

In project appraisal, carbon benefits are often valued in line with the concept of additionality, meaning that only the net

Table 4.1 Carbon prices and sensitivities (2010–2030) for UK policy appraisal, 2014 GBP per tCO_2e.

	Traded			Non-traded		
Year	**Low**	**Central**	**High**	**Low**	**Central**	**High**
2010	13	13	13	29	57	86
2011	11	11	11	29	58	87
2012	6	6	6	30	59	89
2013	4	4	4	30	60	90
2014	0	4	12	30	61	91
2015	0	5	16	31	62	93
2016	0	5	20	31	63	94
2017	0	5	21	32	64	95
2018	0	5	27	32	65	97
2019	0	5	34	33	66	98
2020	0	5	40	33	67	100
2021	4	13	47	34	68	102
2022	8	20	55	34	69	103
2023	12	27	63	35	70	105
2024	16	34	70	36	71	107
2025	19	42	78	36	72	108
2026	23	49	86	37	73	110
2027	27	56	93	37	74	112
2028	31	63	101	38	75	113
2029	35	70	109	38	77	115
2030	39	78	116	39	78	116

Source: DECC Modelling (2014). This table supports the DECC/HM Treasury Green Book guidance on valuing GHG flows. The 'low' and 'high' columns represent bounds for sensitivity analysis.
Traded values for 2010–2013 reflect actual prices. The remaining values are modelled. All values are reported in GBP 2014.

[22] Annual revisions to traded-sector prices are available from https://www.gov.uk/government/collections/carbon-valuation--2 and a spreadsheet-based toolkit with DECC long-term carbon price projections is available from https://www.gov.uk/government/publications/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal

benefits in comparison to the status quo (what would have happened in the absence of the project) are valued. For example, for Woodland Carbon Code projects carbon sequestration for the created woodland is valued up to the long-run average level for the type of woodland created but carbon sequestration provided by existing woodlands is not counted because this would have been provided in the absence of the project.

The carbon sequestered by trees (and woodlands) is stored in tree biomass (trunks, foliage and roots) and soils. This represents a large stock of carbon that is stored in trees and woodlands. For accounting purposes the total stock of carbon, and associated net present value taking into account emissions from the burning and decay of wood products, have been calculated. For example, Davies *et al*. (2011) estimate that 97.3% of the total 231 521 tonnes of carbon stored in vegetation in Leicester is associated with trees. Likewise, Strohbach and Haase (2012) estimate that urban trees in Leipzig provide 316 000 tonnes of above-ground carbon storage. There are many complexities involved in calculating the value of carbon storage; conventional methods relate timber volume to dry weight using individual species densities and then converting this into carbon content. Calculations can be tailored to account for carbon in non-stem components based on tree species, age and woodland management practices. However, additional challenges are raised by leaf biomass, ground vegetation, litter, soil carbon stocks and emissions from harvested wood products.

The Forestry Commission has a well-established model of carbon accounting called CARBINE (Edwards and Christie, 1981, see http://www.forestry.gov.uk/fr/infd-633dxb for further details). CARBINE estimates stocks of carbon stored in trees and released through harvesting as well as avoided greenhouse gas emissions (through the use of wood products that displace fossil fuel intensive materials) and these models can scale from individual trees to entire woodlands, taking into account a range of management practices, such as thinning and felling.

In the National Ecosystem Assessment Follow-On report (Chapter 3a) the additional carbon benefits provided by new planting of Sitka spruce and pedunculate oak woodlands were constructed using CARBINE for carbon in biomass and harvested wood products and information on soil carbon relative to agricultural land use.

Urban cooling

In the urban context, trees and shrubs provide protection from heat and ultraviolet radiation by providing shade (Potchter, Cohen and Bitan, 2006). For instance, using the high emissions scenarios based on the UK Climate Impacts Programme (UKCIP02) predictions, Gill *et al*. (2007) project that increasing the existing green infrastructure in Greater Manchester by 10% in areas with little or no cover could reduce temperatures by up to 2.5 degrees Celsius.

Several US-based studies estimate economic values for cooling services by shade trees in urban settings (Akbari 2002; Nowak *et al*., 2010, 2012). Using data on indoor and outdoor temperature and humidity, wind speed and direction and air-conditioning cooling energy use, Akbari *et al*. (1997) showed that shade trees near houses can yield seasonal cooling energy savings of approximately 30%. Similarly, Konopacki and Akbari (2000) found that the cooling effects of trees (from both shading and evapotranspiration) could generate net annual dollar savings in energy expenditure of US$ 6.3 million, US$ 12.8 million and US$ 1.5 million for Baton Rouge, Sacramento and Salt Lake City, respectively (Akbari, 2002). More recent studies in Chicago (Nowak, 2010) and Toronto (Nowak *et al*., 2012) identify annual residential energy savings due to shade trees of US$ 360 000 per year and CAD 9.7 million per year, respectively.

The figures on residential energy savings from North American studies are sufficient to suggest that this could be a useful area of study for the UK. Given the relative temperatures and prevalence of air conditioning in North America relative to the UK, it is possible that energy savings may be lower in the UK. However, if future studies also incorporated potential health impacts (of reducing urban heat islands during summer heatwaves, reduced dehydration and heat stroke), the overall value of urban cooling services from trees could remain substantial.

Research gaps

The effect of trees on global climate is relatively well studied, particularly in terms of GHG flows. However, for the UK there is a need for more valuation research on the impact of trees on urban heat islands, as well as on reducing building energy use. Future research needs include:

- Improved estimates of the social cost of carbon (carbon price). This is an active area of research, but is unlikely to be resolved in the short or medium run. As such, employing UK Government carbon prices is a straightforward compromise.
- Estimating the effect of trees on urban heat islands (through shading and evapotranspiration) in UK cities.
- Linking urban cooling services in UK cities to energy savings.

5. Recreation

Biophysical evidence	Valuation evidence	Decision support tools	Urban tree literature
Large-scale time-series studies such as Monitoring of Engagement with the Natural Environment (MENE) have provided rich data on the relationship between site characteristics and recreational visits.	Complex valuation methods for analysing recreational behaviour are available; these methods make use of spatially explicit data and are able to account for the availability of substitute sites as well as providing information on use and non-use values.	Research has the potential to substantially improve decision-making in this area. Improved decision-making tools are needed to support urban planning and the management of recreational sites.	The evidence for recreational values from urban trees and woodlands is relatively robust (Brander and Koetse, 2011; Perino *et al.*, 2014); however, none of the urban valuation tools reviewed here currently incorporate recreation into their valuation calculations.

Key: Strong evidence | Good evidence but some gaps | Major gaps in evidence

Biophysical pathways

Trees and forest are connected to recreation through a number of pathways:

- Trees are recreational site characteristics: Trees and forests are defining characteristic of recreational sites and, as such, enter the production of recreation directly. In this capacity, trees and forests facilitate a wide range of recreational pursuits, including walking, cycling, horse riding, camping, fishing and bird watching.
- Trees modify the quality and availability of sites: Recreational demand has been shown to vary according to the nature of the forest recreation site such as the size and type of woodland, facilities and the recreational activities available on site (Jones *et al.*, 2010). Woodland also indirectly influences recreation through its modification of other final environmental goods and services that influence the quality and availability of recreation sites. These include water quality (through opportunities for recreational fishing, swimming or boating), air quality (through health effects or visibility), climate/temperature (through shading, cooling and shelter from extreme weather) and biodiversity (through bird watching or nature viewing).
- Recreational activities affect the biophysical functioning of trees and woodlands: Recreation as an activity can also affect the natural environment and the provision of final environmental goods and services. For example, recreational activities can cause wildlife and habitat disturbance (Marzano and Dandy, 2012). This conflict between habitat conservation and recreation can be exacerbated at open access sites due to visitor preferences to avoid overcrowding (Tratalos *et al.*, 2013).

Recreation units

Two units of measurement are key to valuing the contributions of trees and forests to recreational experiences – the marginal (per visit) value of the site and the quantity of visits to each site:

- Value: The marginal contribution that environmental quality makes to the value of recreational experiences is frequently estimated using the travel cost method (Willis and Garrod, 1991; Benson, 1994; Zandersen and Tol, 2009). The travel cost method models the environmental quality of recreational sites along with a series of complementary site characteristics and market goods, most notably the cost of travelling to the site. Since the quality of the natural area cannot be enjoyed without the market purchases,[23] those purchases provide information on the value households place on environmental quality. Accordingly, people's expenditure on travelling to sites provides information that can be used to deduce economic value.
- Trips: The quantity of visits made to a site has typically been estimated through the undertaking of large-scale visitor surveys. However, this form of data collection is a very time consuming and expensive process. More recently, researchers have developed models to predict visitation

[23] Travel cost methods tend to focus purely on the cost of travelling to the site; however, it is also likely that access to recreational sites is capitalised into property prices. As a result, residents living in close proximity to woodlands may pay a premium on their property prices, which provides them with access and eliminates the need for expenditure on travel. For these residents a pure travel cost method will tend to underestimate the recreational value of woodlands; however, the omitted value would be captured through hedonic price analyses, although it may be difficult to disentangle the recreation component from other social and environmental benefits provided by proximity to trees and woodlands (e.g. amenity value and health benefits).

rates. For example, Jones, Bateman, and Wright, (2003), and Jones *et al*. (2010) developed a model which takes account of the accessibility, facilities, availability of substitutes and variation in population characteristics. They found that accessibility (defined by travel time) was the strongest predictor of visitor numbers but also observed significant substitution effects for alternative recreation sites and activities. Similarly, Sen *et al*. (2011) developed a trip generating function to predict the annual number of visitors that would arrive at a new woodland. Combined with national population and geographic databases these models can provide estimates for the quantity of visits to recreational sites without the need for costly visitor surveys.

Economic production functions

Recreational activity also enters a number of other environmental, household and firm production functions, for example:

- Biodiversity – recreational activity impacts on conservation and habitat, and is a source of disruption to wildlife
- Housing – access to recreational sites and urban greenspace is a sought after amenity, and this is reflected through property premiums
- Physical health – through the use of greenspace for physical exercise including walking and cycling
- Mental health – access to and recreational use of greenspace has been linked to reductions in stress and tension
- Artistic – as an input to or inspiration for the production of art by amateur and professional artists
- Learning – opportunities for educators, students and researchers to learn from and experience the environment
- Spiritual and cultural – for spiritual, ceremonial or celebratory purposes
- Non-use value – the benefits trees provide for people who care about existence value of the environment (those who think it is important to preserve the environment for moral/ethical connection or fear of unintended consequences) or bequest values (those who think it is important to preserve the environment for future generations)

Beneficiaries

The beneficiaries of improvements to recreational sites are broadly categorised as recreational businesses, recreational users and members of the general public who benefit through non-use value.

Valuation methods

In modelling demand for woodland recreation the key methodology is the travel cost approach. The travel cost method models the environmental quality of recreational sites along with a series of complementary market goods, most notably the costs of travel to the site. Data are often collected on site and frequently at locations close to on-site facilities, such as car parks, visitor centres and toilets. The approach to data collection is important for the analysis of travel cost data, in particular the quality of on-site facilities needs to be accounted for and care should be taken when scaling up the number of trips across areas of the site with different (or no) facilities. A second limitation of the travel cost method is that it does not extend easily to situations in which consumers are faced by an array of substitute recreational sites. In those circumstances, the consumers are as concerned with the choice between sites as the choice of the number of trips to take to one particular site. The standard method applied in the case of multiple sites is provided by the random utility model: a discrete choice modelling technique in which consumers are assumed to choose which particular site to visit based on the qualities of, and costs of travel to, the different sites available to them.

One particularly useful dataset for creating models of woodland recreation valuation in the UK is the one utilised in the UK NEAFO project – the Monitor of Engagement with the Natural Environment (MENE) survey. The survey takes a representative sample of English adult residents, and uses diary records of their recreational trips in the week running up to the interview date. The survey started in 2009 and every year over 45 000 interviews are recorded. It gathers national-level data for all forms of recreation involving the natural environment. This allows for discrete choice models to be built (as in the UK NEAFO project) that capture the impacts of substitute availability, therefore avoiding the overestimation of values which would arise if substitution effects were ignored. In addition, it records data not just for those people who undertake recreational activity but also for those people who do not undertake any; this is different to typical travel cost surveys in which only those people who visit the recreation site are included in the survey.

An alternative to the travel cost approach is to attempt to value directly the recreational benefits using stated preference techniques such as the contingent valuation method. Often, stated preference studies include attributes of the woodland or forest and individual characteristics but fail to account for off-site characteristics such as substitute sites and the geographical distribution of sites. This causes two problems: (i) value estimates which do not take in accessibility of substitutes may be biased and (ii) value functions based on small-scale on-site surveys may have limited transferability outside the specifics of the study.

Another option is to transfer the economic values from a previous study. Of course, it is highly unusual that an existing study will provide the perfect fit in terms of both attributes and context. Indeed, the usual procedure would be to attempt to adjust values from the original study in order to account for differences in the attributes and context of the situation in which they are to be applied. Ideally, we would like those adjustments to be driven by empirical evidence, perhaps in the form of a transfer function; that is to say, a function that indicates the relationship between levels of value and different levels of attributes and context. A second approach to developing transfer functions is provided by the method of meta-analysis. Meta-analysis is a statistical approach in which valuations drawn from multiple original studies are combined and analysed in order to identify how estimates differ as a result of differences in the attributes of the FEGS being valued and differences in the context in which they were consumed. Meta-analyses will often also examine whether the values differ systematically according to the valuation method used in the original studies and/or differences in the methods of data collection and analysis.

Valuation scale

- Bateman, Abson *et al*. (2011) and Bateman, Day *et al*. (2014) show how location of recreational sites matters. A specific and moderate-sized nature recreation site, for example, might generate values of between GBP 1000 and GBP 65 000 per annum, depending solely on where it is located. The critical determinant of this range is, perhaps not surprisingly, proximity to significant conurbations. Put another way, woodlands in the 'right' place (i.e. relatively close to potential visiting populations) are likely to give rise to higher social values (other things being equal), an insight of particular importance if policy-makers are contemplating new investments in these nature sites.
- Bartczak *et al*. (2008) show the dangers of transferring values across different countries in their travel cost national study of Poland. They show that forest recreation is valued highly in Poland (EUR 0.64–6.93 per trip per person) with trip frequency and values higher than Western Europe despite lower income levels.

Valuation estimates

The Woodland Valuation Tool currently contains 29 valuation studies and 6 biophysical studies relating to recreation.

Recreational users

Valuing the contributions of trees and forests to recreational users is a well-studied problem. In Table 5.1 we present the

Table 5.1 Recreation values from the existing evidence base.

Source	Value per visit (converted to 2014 GBP)	Values for	Method/notes
Scarpa (2003)	2.23–3.69	Forests and woodlands only	Contingent valuation (open-ended and dichotomous choice willingness to pay surveys).
Christie *et al.* (2006b)	9.75–18.50	Forests and woodlands only	Travel cost method to estimate the value of improvements to recreational facilities in forests. Range depends on type of recreation activity (e.g. cycling, hiking).
Eftec (2010)	2.69	Forests and woodlands only	Low facility sites; constant value applied per trip. Does not vary with size of woodland, distance from populations, household incomes, availability of substitutes and so on.
Eftec (2010)	13.45	Forests and woodlands only	High facility sites; constant value applied per trip. Does not vary with size of woodland, distance from populations, household incomes, availability of substitutes and so on.
Sen *et al.* (2012)	3.35*	All outdoor recreation types across Great Britain, including forests and woodlands	Meta-analysis of over 100 studies, combining revealed and stated preference valuation techniques. Develops detailed Trip Generation Function (TGF**). Expressly models travel time and cost from each potential outset area to each recreation site, availability of substitute sites and household characteristics (e.g. income).
Sen *et al.* (2014)	3.59	Forests and woodlands only	Combines TGF with meta-analysis of 297 values from 98 studies to estimate per visit values. Expressly models travel time and cost from each potential outset area to each recreation site, availability of substitute sites and household characteristics (e.g. income).

Notes: Conversions to 2014 GBP using HM Treasury GDP Quarterly Deflators 30 September 2015 Update, available from: https://www.gov.uk/government/statistics/gdp-deflators-at-market-prices-and-money-gdp-september-2015-quarterly-national-accounts. * Based on Sen *et al.* (2012) base case scenario with 3231 000 visits totalling GBP 10 040 000 in value. ** The TGF developed in Sen *et al.* (2011) relates the number of trips observed to a variety of predictor variables including site type (e.g. mountain, lake, grassland); study details (sample size, treatment of substitutes, valuation methods); demographic details (population density). Some studies excluded due to age.

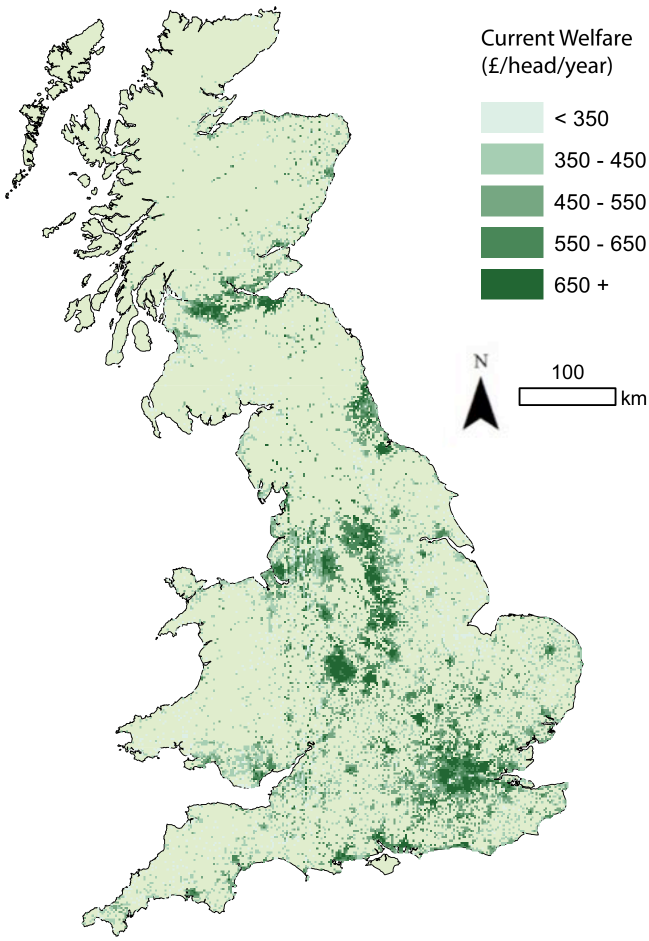
marginal (per visit) per person values for recreational users of woodlands and forests from a number of recent UK studies. The values are estimated using a range of techniques. For example, Scarpa (2003) used two stated preference techniques (an open-ended contingent valuation survey and a dichotomous choice contingent valuation survey); Christie *et al*. (2006b) combined stated and revealed preference techniques including the travel cost method; Eftec (2010) applied two constant values depending on whether the recreation site has a high level of facilities or a low level; and Sen *et al*. (2012, 2014) used a meta-analysis to transfer previous value estimates.

The values reported in Table 5.1 range from GBP 2.23 up to GBP 18.50 (in 2014 GBP). The environmental valuation literature has demonstrated that there are many determining factors of forest recreational value (Scarpa, 2003; Scarpa *et al*., 2007), including the accessibility, facilities and variation in population characteristics and socio-economic factors. The highest values reported in the table are for specialist users of the woodlands from Christie *et al*. (2006b); they show that cyclists, horse riders and walkers all value forest recreation highly. Furthermore, Christie, Hanley and Hynes (2007) employ a combination of revealed and stated preference methods to value the component attributes of forest recreation, valuing specific enhancements for different recreational users. For example, they report the largest increase in value would be for new family play areas (GBP 8.75 per visitor per year in 2005 GBP) and new wildlife hides for nature watchers (GBP 7.89 per visitor per year in 2005 GBP). In addition, they report expected changes in the number of trips to the recreational forest; the largest proportional changes in trips come from investing in new family play areas (10.2% increase) and investing in new trail obstacles for cyclists (5.0% increase).

However, capturing the economic values of individual forest sites is not only a matter of knowing the site characteristics and the socio-economic characteristics and preferences of the population. The spatial locations of the recreational site and of substitute sites are also important. Figure 5.1, which is from the UK NEAFO (Bateman, Day *et al*., 2014), maps the current annual welfare for the set of outdoor recreation opportunities available across Great Britain. The figure shows that significant differences occur across Britain (values range from a low of GBP 258 to a maximum of GBP 959 per person per year in 2014 GBP), reflecting the differences in the availability of recreational opportunities.

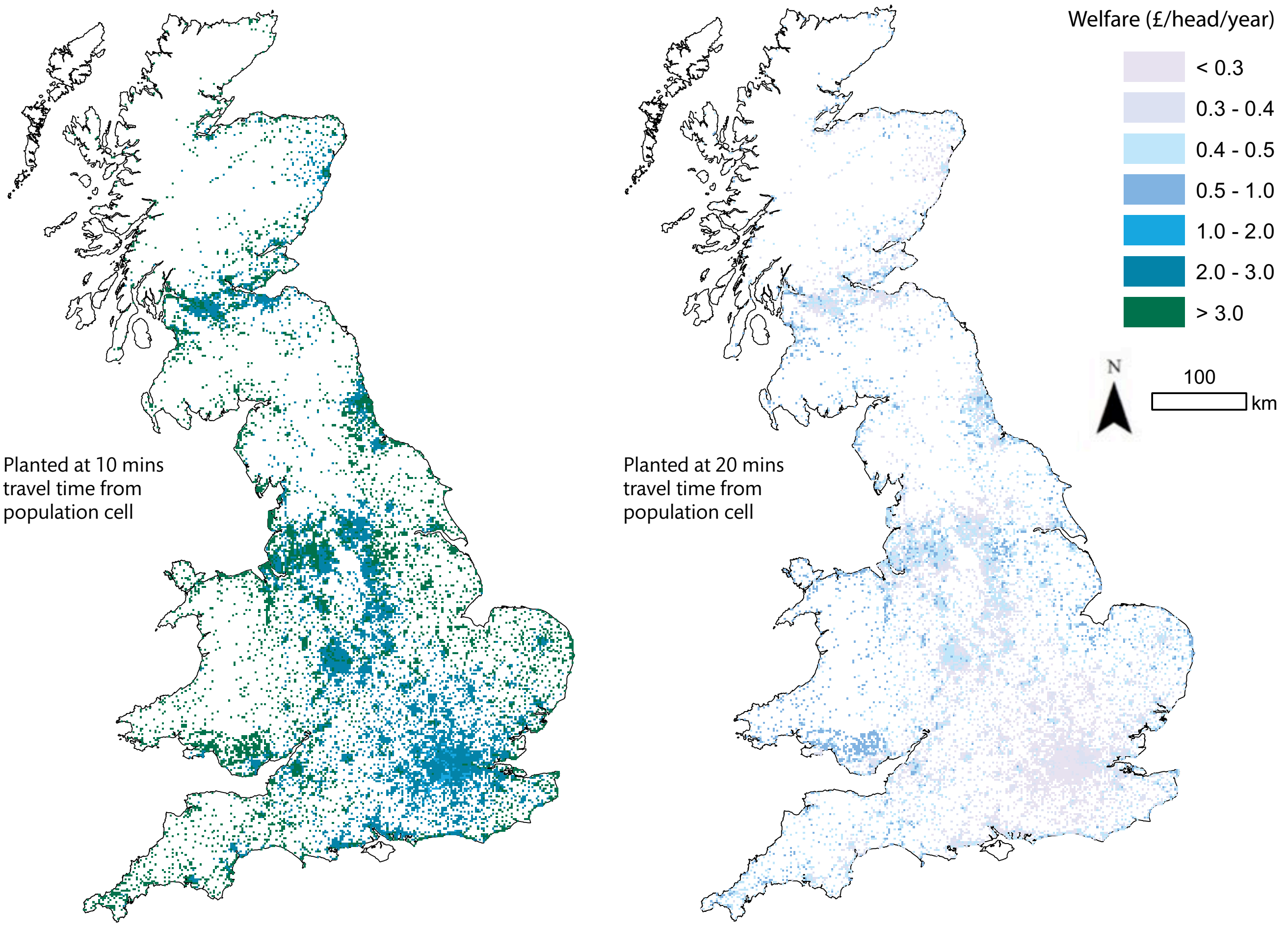
As part of the UK NEAFO project a model was developed which distinguishes between the benefits that come from woodland recreational sites in the context of all alternative outdoor recreation opportunities (substitute sites). To make

Figure 5.1 Annual welfare benefits from access to current set of outdoor recreation opportunities.



that distinction the model has to be able to capture distance decay (that the benefits enjoyed from a recreational woodland decline with increasing distance) and the availability of substitute recreation sites (that the benefits decline with an increased availability of alternative recreation opportunities). Figure 5.2 illustrates a hypothetical scenario of 100 ha of new planting planted at a distance of 10-minute travel time (for driving) from each population centre on the left and 20-minute travel time on the right. The average annual welfare gain for the woodland located 10 minutes from population centres is GBP 3.02 per person per year in 2014 GBP, while the average annual welfare gain for the woodland located 20 minutes from population centres is GBP 0.29 per person per year in 2014 GBP. This shows clearly the importance of spatial location, particularly proximity to heavily populated areas, on the economic value of new woodland recreation sites. In addition, the per person welfare gains vary across Britain; for example, the per head welfare gains appear to be relatively lower in London than they are in areas of northwest England or South Wales and this can, at least partly, be explained by the differences in availability of substitute outdoor recreation opportunities.

Figure 5.2 Annual per person welfare gains from access to newly planted woodland.



Research gaps

- Values associated with recreation need to be broken down to reveal differences in willingness to pay for different recreational users (e.g. joggers, cyclists, fishermen/women, hunters).
- Urban trees and woodlands provide opportunities for recreational experiences in an urban landscape, which is a mosaic of different land uses and in close proximity to densely populated residential and commercial areas. The evidence for recreational values from urban trees and woodlands is relatively robust (Brander and Koetse, 2011; Perino *et al*., 2014); however, none of the urban valuation tools reviewed here currently incorporate recreation into their valuation calculations.
- Bateman, Abson *et al*. (2011) and Bateman, Day *et al*. (2014) show how location of recreational sites matters. A recreational site can generate a significant range in values depending on where it is located. The critical determinant of this range is, perhaps not surprisingly, proximity to significant conurbations, and thus the study of recreation values in urban areas is particularly salient.
- Improved decision-making tools are needed to support urban planning and the management of recreational sites.
- A greater understanding and modelling of the contextual drivers of recreational demand, including weather, are needed.

6. Physical and mental health

Biophysical evidence	Valuation evidence	Decision support tools	Urban tree literature
A fundamental challenge is the need to establish causality, substitution and response behaviours between trees/woodland (as opposed to other environments) and mental and physical health.	There is no commonly applied generic measure for mental health. This makes comparison between biophysical studies difficult and the lack of a well-defined and commonly understood mental health good or service poses a challenge for valuation.	The evidence base needs to be developed to facilitate the development of accessible decision support tools that incorporate mental health and physical health impacts resulting from activities beyond habitual exercise.	The key challenge in valuing the physical and mental health benefits provided by urban trees and woodlands lies in developing a clear understanding of the biophysical processes at work and understanding whether these relationships hold, or are augmented, for urban trees as a subset of greenspace.

Key: Strong evidence | Good evidence but some gaps | Major gaps in evidence

Biophysical pathways

Woodlands have been shown to affect physical and mental health through their impact on final environmental goods and services including clean air, clean water and presence of natural environment. Mourato *et al*. (2010) identify three pathways through which environmental amenities and the natural environment affect physical and mental health. These are:

1. Through the absorption of pollutants (e.g. air pollutants including SO_2).
2. By acting as a catalyst for healthy lifestyle choices such as exercising regularly.
3. Through health benefits provided by exposure to a natural environment (e.g. reduced stress and tension).

The direct health benefits associated with trees and woodlands include:

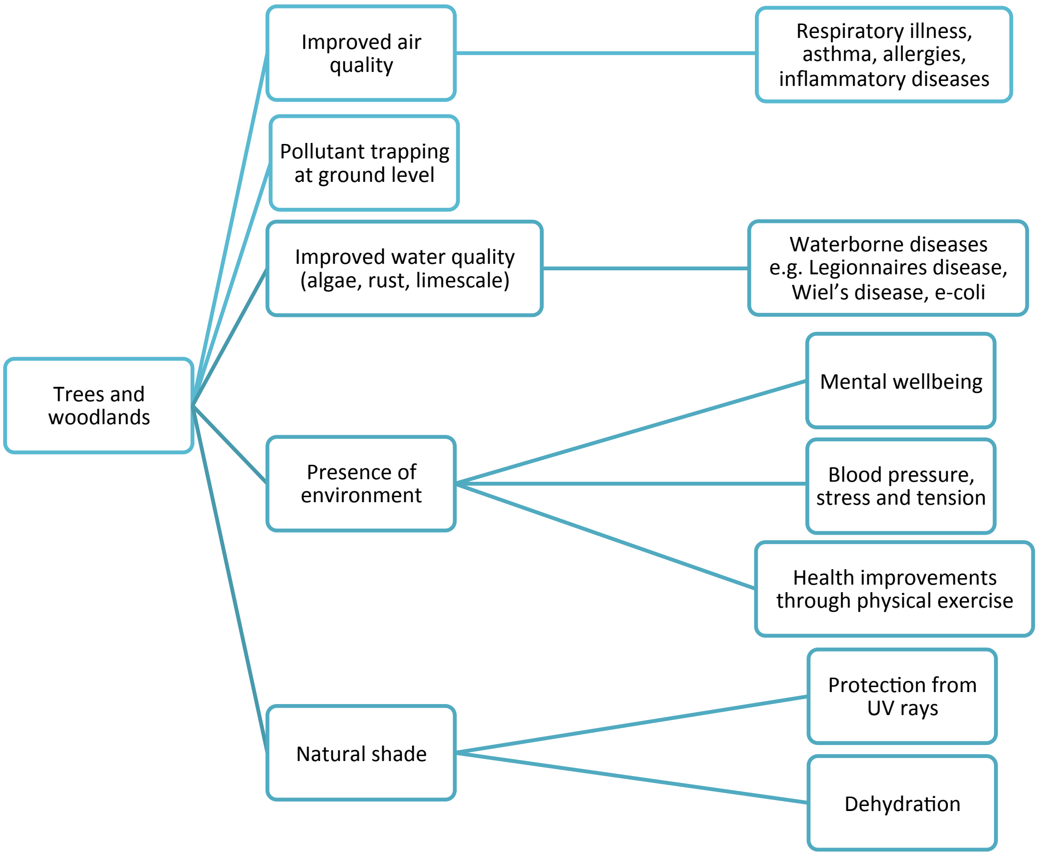
- Fewer respiratory illnesses/diseases, hospital visits and early deaths associated with air pollution (Powe and Willis, 2004, 2002).
- Reduced incidence of asthma, allergies and chronic inflammatory diseases in children Ruokolainen *et al*. (2015).
- Better health through improvements in water quality at recreational sites and thus fewer instances of waterborne diseases such as *Legionella*, *E. coli* and Weil's disease.
- Fitness-related benefits associated with green exercise, including exercise through recreational activities such as biking, walking and fishing. These include reduced risks of heart attacks, type 2 diabetes, strokes, breast and colon cancer, osteoarthritis, obesity, depression and dementia (Bird *et al*., 2003; Pretty *et al*., 2005, 2007; Cook, 2015). Mitchell and Popham (2008) found that circulatory diseases and mortality rates from all causes were decreased in populations exposed to greener environments (including woodlands).
- Reduced ultraviolet radiation (Potchter, Cohen and Bitan, 2006).
- Less dehydration – through the provision of shade and protection from heat (Potchter, Cohen and Bitan, 2006).
- Fewer mental health problems including stress and anxiety (Hartig *et al*., 2003; Maller *et al*., 2006; Annerstedt *et al*., 2012; Alcock *et al*., 2014). However, Milligan and Bingley (2007) show that woodlands can create anxiety and uncertainty in some people and that benefits or losses to welfare from woodlands vary depending on the individual.
- In addition, tree diseases and losses due to pests have recently been associated with increases in cardiovascular disease in women (Donovan *et al*., 2013; 2015), suggesting a link between healthy disease and pest free trees and lower rates of cardiovascular disease.

The pathways through which trees and woodlands affect health are depicted in Figure 6.1.

Physical and mental health units

As was discussed in the air quality section (Section 3), physical health is often directly valued by calculating the change in the number of hospital visits, deaths avoided by one year, changes in quality of life years and/or changes in morbidity and mortality risks (Powe and Willis, 2002; Willis *et al*., 2003). Mental health outcomes are measured less uniformly. The Department of Health's Expert Group on mental health outcomes identified a number of widely used measures, including HONOS, CORE-OM, GHQ, BDI, Lancashire Quality of Life Scale, CAN, FACE, MHI-5 (from the SF-36) and MANSA. These measures are often used in clinical trials and

Figure 6.1 Biophysical processes of woodland influencing health.



some relate to specific mental health illnesses and were not designed with valuation in mind. The size and complexity of these measures makes them unsuitable for use in preference elicitation studies. Brazier (2008) argues that the development of a generic preference-based mental health measure for valuation is a much needed and important advancement.

Economic production functions

Physical and mental health can also enter a number of other production functions as contextual variables. For example, the health of a labour force affects their productivity and, as a result, has an impact on the production of goods and services. A simple way to think about this is to see health as a type of technology in a production function; this technology can enhance or hinder the productivity of labour (output per hour of labour) and can alter the structure of (or preferences in) a utility function.

For example, health can affect:

- Food and industrial production – productivity levels are dependent on the health and well-being of the labour force
- Recreation – ability to take part in and the value derived from recreational activities can be affected by physical and mental health
- Artistic production – the production of and value derived from art is dependent on the health and well-being of the artist and of the audience
- Learning experiences – opportunities for educators, students and researchers to learn from and experience the environment
- Spiritual and cultural experiences – for spiritual, ceremonial or celebratory purposes
- Utility functions – health has been shown to affect willingness to pay for reductions in mortality risk in US stated preference studies (Krupnick *et al*., 2002)

Beneficiaries

The general public and healthcare providers benefit from improvements in physical and mental health.

Physical and mental health are controversial; there is an ongoing debate about whether they enter a person's utility function directly as a final good or service (i.e. people derive value from the fact that they are healthy), or whether they enter indirectly through altering the production of utility from other goods and services. For instance, the utility derived from a recreational visit to Thetford forest depends on a person's health, and they will derive less utility from the visit if their asthma is bad due to poor air quality, or if they are suffering with hay fever due to high levels of pollen in the air. Of course, it is possible that both of the explanations are true.

The existing empirical and valuation literature approaches good health (or the avoidance of bad health) as though it is a final good and service and largely ignores any impact that health may have on the value of other goods and services. As a result, gains in economic value that could be achieved through improving health and indirectly increasing the value of existing consumption are being overlooked.

Valuation methods

Stated preference methods, social damage cost functions, replacement cost methods and cost-efficiency measures (e.g. National Institute for Health and Care Excellence, or NICE, guidelines for medical treatments) have all been used to value health benefits.

Economic assessment tools for valuing health benefits are also available. For example, the Health Economic Assessment Tool (HEAT) is available from the World Health Organization Regional Office for Europe. HEAT provides values for the benefits in terms of mortality rate improvements derived from habitual walking and cycling as recreational activities using the UK Value of Statistical Life discounted by a default discount rate of 5%.[24] However, the tool does not disaggregate the benefits by particular types of green infrastructure. As a result, reporting the total value will overstate the benefits from urban trees and woodlands, or alternatively scaling for the proportion of total green infrastructure that is trees and woodland makes the assumption that green infrastructure is perfectly substitutable. In addition, HEAT does not include broader physical health benefits, such as improvements to quality of life, or mental health benefits, and is not suitable for valuing the benefits of one-off activities (e.g. non-habitual cycling).

Valuation scale

Studies linking tree and woodlands to health tend to be highly localised; for example Powe and Willis (2002) assess air quality effects of trees at the 1 km^2 scale, focusing on woodlands of 2 ha or more. The i-Tree model developed by the US Forest Service has been applied from the level of individual trees to city-wide assessments (Hutchings, Lawrence and Brunt, 2012; Rumble *et al*., 2014), and Willis (2015) examines the relationship between woodlands and mental health through a case study in Scotland. However, estimates of the monetary value of improved health, be it reductions in hospital visits, medical bills or risk of mortality, are more frequently conducted at a national scale where an average unit value is applied.

[24] Users are able to override this default value, and we recommended using the official UK Treasury procedure for discounting.

Valuation estimates

The Woodland Valuation Tool currently contains 14 valuation studies and 21 biophysical studies relating to physical and/or mental health.

The existing values relating woodlands and trees to both physical health and mental health can be divided into those relating to the general public and those relating to healthcare providers.

Physical health

General public

- Stated preference-based values for avoided illness: As was discussed in Section 3, the health benefits of improved air quality have been estimated by Powe and Willis (2002, 2004). Both Willis *et al*. (2003) and Eftec (2011) report the Powe and Willis (2002) values of GBP 124 998 for each death avoided by one year due to PM_{10} and SO_2 absorbed by trees, and GBP 602 for an 11-day hospital stay avoided due to reduced respiratory illness (in 2002 GBP).

Likewise, HEAT provides values for the benefits derived from habitual walking and cycling as recreational activities. More details are given on page 80.

Healthcare providers

Social costs of pollutants: These are calculated by estimating externality and social damage costs for a given unit of pollution reduction. The social damage costs incorporate health costs associated with the pollutant. One common example is the social cost of carbon (see Section 4 on climate for further details), and similar values are employed in i-Tree which applies a monetary value in pounds per tonne of PM_{10}, $PM_{2.5}$, NO_2, SO_2 and O_3 (Hutchings, Lawrence and Brunt, 2012; Rumble *et al*., 2014).

An alternative approach to estimating benefits to healthcare providers is to consider the financial impact on healthcare providers by estimating cost savings in relation to alternative medical treatments (e.g. reduction in medical bills, prescriptions). This approach is generally foregone in favour of per unit social costs due to their ease of use and standardisation.

Mental health

General public

Stated preference methods have been adopted as one way of monetising the health benefits provided by the environment, including trees and woodlands. Some studies, such as those employed in HEAT (see above) are derived from stated preference questions relating to general health benefits, therefore potentially encompassing both physical and mental health benefits. Such willingness to pay estimates also underpin the Department of Health's monetary values for the health benefits associated with reductions in PM_{10} and SO_2 (Powe and Willis, 2004, 2002; Chanel and Luchini, 2014). Other studies attempt to estimate the general public's willingness to pay specifically to avoid mental illnesses; for example, Smith, Damschroder and Ubel (2012) report a monthly willingness to pay to avoid depression of US$ 76.90 in 2006 US$) or for reductions in mortality risk (Krupnick *et al*., 2002).

Brazier (2008) provides a concise review of the issues of what aspects of health and well-being should be valued, how they should be described and how they can be valued. In particular, Brazier (2008) discusses the potential to develop mental health QALYs (Quality Adjusted Life Years) from an existing measure of mental health, the CORE-OM, using modern psychometric methods to construct health states amenable to valuation. Initial evidence suggests that generic measures may be adequate for capturing preferences for avoiding depression and anxiety, but not for psychotic and complex conditions.

An additional complexity in the valuation of mental health benefits arises due to the fact that reported willingness to pay appears to be different for healthy members of the general public versus patients, with those suffering from mental illness willing to pay more to avoid mental health issues (Brazier, 2008). This can cause a divergence between willingness to pay values aggregated from stated preference studies from the general public versus patients and has implications for evaluating the cost-efficiency of interventions/schemes.

Healthcare providers

As mentioned above, an alternative approach to estimating health-related benefits is to consider the financial impact on healthcare providers by estimating the cost savings achieved from, for example, a reduction in medical bills and, prescriptions (including antidepressants and counselling for mental health illnesses), when people choose other forms of health care and treatment.

More recently, the relationship between woodlands and mental health have been explored through case studies. For example, Willis (2015) provides a Scottish case study exploring health-related quality of life improvements from woodland group-based activities. Willis (2015) finds that 'The Branching Out' programme leads to a QALY improvement in the short term.

The evidence base relating woodlands to mental health improvements is weak but developing. Individual case studies require the collection of detailed information sustained over a long period of time for both treatment and control groups. The introduction of a generic mental health measure could also serve to facilitate comparisons across studies and reduce the number of control groups required.

Research gaps

Eftec (2011) identified the key gap in this area to be in relating the dose–response biophysical information on the natural environment and health outcomes to specific influences of trees and woodlands. This gap remains the most challenging for valuing the health benefits of woodlands. However, there are a number of additional gaps and challenges for both physical and mental health and these are noted below.

Physical health

Waterborne diseases: Risk of disease is likely to be an element of willingness to pay for improvements in water quality at recreational sites; however, waterborne diseases have not been studied directly in the literature surveyed in this study.

Mental health

Compounded values and double counting: Health is included in recreation and may form a part of values for the consumption of other goods and services by altering preferences. The health-related values are difficult to disentangle from values in the existing literature and there is a risk of double counting these values, for example if willingness to pay for recreational visits is combined with willingness to pay for health benefits associated with the use of recreational spaces.

Measuring mental health units: There is no commonly applied generic measure for mental health. This makes comparison between biophysical studies difficult and the lack of a well-defined and commonly understood mental health good or service poses a fundamental challenge for valuation.

7. Biodiversity

Biophysical evidence	Valuation evidence	Decision support tools	Urban tree literature
The need for improvements in the economic valuation of biodiversity needs to be matched by better data and natural science understanding of the physical impacts of afforestation upon measures of biodiversity and human health.	A particular problem arises regarding estimation of the non-use benefits of biodiversity where the lack of behavioural action precludes the use of revealed preference methods.	The measurement of biodiversity, biophysical evidence base and robust valuation methods need to be established before meaningful decision support tools that incorporate biodiversity can be developed.	While there is evidence to suggest that urban woodlands and domestic gardens promote biodiversity in towns, the biodiversity related benefits provided by urban trees are not well understood and do not form part of the values reported by tools such as i-Tree Eco.

Key: Strong evidence | Good evidence but some gaps | Major gaps in evidence

The concept of biodiversity refers to the variety of life forms that are supported by and in part define an ecosystem. Biodiversity then is a measure of an ecosystem's biological complexity and should be distinguished from the constituent forms of life (including flora, fauna and fungi) that exist in that ecosystem.

Despite the clear definitional difference between wild species and biodiversity, a number of studies focus upon the former rather than the latter. In part this is understandable because various measures of biodiversity exist. Furthermore, some studies deliberately use certain wild species, such as birds and large mammals, as proxy indicators for wider biodiversity. This is a common simplification and clearly has empirical attractions given the complexities of evaluating and measuring biodiversity, but we should remember that these are not the same and indeed the choice of such indicator species is often contentious.

A somewhat different issue arises where the focus of a valuation study is not biodiversity but rather some individual 'iconic' species. From an economic perspective this might be perfectly reasonable if that single species is the object which generates value. In such cases biodiversity may only be of value to the extent that it supports the provision of that particular species. However, the relationship between the biodiversity of an ecosystem and a given species is typically complex. Food webs and other intermediate environmental services mean that species typically depend on a variety of interrelationships. For example, the endangered Sumatran tiger has been the focus of valuation studies (Bateman *et al*., 2009), but is highly dependent upon a variety of other species such as the wild pig. Damaging one element of this web can generate far-reaching impacts on multiple species which are often difficult to predict.[25] In such cases the conservation of biodiversity might provide a necessary element of ensuring the continued existence of a valued individual species.

Biophysical pathways

Woodlands and forests embrace an amalgamation of complex, long-standing ecological relationships which are reflected in the biodiversity of such environments. Within Great Britain woodland assemblages have developed in relation to climate, soils, biotic interactions and long-standing human interference. Changes to environmental and human determinants are likely to lead to changes in woodland ecosystems and their biodiversity. Here we briefly consider three key drivers of change: (i) the planting of new woodlands and trees, (ii) the management of woodlands and (iii) the effects of climate change. These drivers affect forest biodiversity and its role as an intermediate and final ecosystem good and service.

(i) Planting new woodlands and trees

Within the UK context the most recent interdisciplinary assessment (linking natural science with economic valuation) of the impact of woodland planting upon an indicator of biodiversity was undertaken as part of the UK National Ecosystem Assessment (UK NEA, 2011) and its 'follow-on' (UK NEAFO) programme (Albon *et al*., 2014). In both of these analyses biodiversity was assessed through

[25] As an example, the decimation of the Californian sea otter in the 19th century removed a key predictor of sea urchins whose population duly exploded causing devastation to the kelp forests upon which it lived and the eventual collapse of the ecosystem.

indices of various indicator bird species (Hulme and Siriwardena, 2011; Bateman, Harwood *et al*., 2013, 2014). This approach was adopted due to the relatively poor cross-sectional and time-series data available for wider measures of biodiversity, a factor which marks out a significant research gap for future assessments. Both the UK NEA and UK NEAFO programmes consider estimates of the impacts of land-use change out to the 2060s. A baseline counterfactual is established in which land use only responds to expected changes in climate. This analyses reveals substantial losses across all indicator species as growing seasons become warmer and drier. This baseline can be criticised for focusing upon native species and failing to consider the impact of new species migrating to the UK as the climate changes. Nevertheless, from an economic perspective the former losses are relevant if preferences favour the preservation of native species.

Building on this baseline, the UK NEA analysis considers a number of scenarios of land-use change. For all cases envisaging an increase in woodlands the analyses (not surprisingly) predict relative increases in woodland bird species and declines in other species, The UK NEAFO analysis adopts a somewhat different approach in that it seeks to optimise the value of land-use changes subject to a localised 'no-loss' constraint upon biodiversity. However, even within this the impact of afforestation is, again, to favour woodland over other species. This is hardly surprising but underlines the basic systems nature of biodiversity; the advancement of one species or group will often be to the detriment of others. Of course there are many forms of land use which, to some extent or other, will cause the detriment of most or even all aspects of biodiversity.

(ii) Management impacts upon woodland and tree-related biodiversity

No truly natural woodlands remain in Great Britain today (Forestry Commission England, 2010). Therefore woodland biodiversity is, to a greater or lesser extent, a product of human intervention. In assessing the effect of forest management on biodiversity, Paillet *et al*. (2010) conducted a meta-analysis of differences between managed and unmanaged forests in Europe using species richness (defined simply as the number of species present) as a measure of biodiversity. They found species richness to be slightly higher in unmanaged forests than in managed forests with species who rely on continuous forest cover, deadwood or large trees (such as nonvascular plants, fungi and beetles) adversely affected by forest management. In contrast, certain vascular plant species were positively affected. Paillet *et al*. (2010) did not distinguish between the types of management activities used in managed forests, and there exists a gap in knowledge about the specifics of forest management that adversely affect species richness.

Relative to other European forests, in Great Britain there exists a lack of diversity in the dominant canopy tree species (Berry, Onishi and Paterson, 2012). Indeed, planted forests dominated by coniferous tree species, such as Sitka spruce and Scots pine, make up over half of the 3.16 million hectares of woodland in the UK. However, this does not necessarily translate to a lack of diversity in the flora, fauna and fungi supported by those forests (Humphrey, Ferris and Quine, 2003) and these authors suggest that there is scope for improving habitat quality and contributing to UK biodiversity through investments in expanding planted woodland. Furthermore, Brockerhoff *et al*. (2008) note that the question of whether plantations enhance or deplete biodiversity is not a simple one to answer. They propose a series of essential questions that should be considered including: What was the land use that preceded the plantation? How does plantation forestry compare with alternative land uses for that particular location? Does the plantation lead to reduced harvesting of native tree species? How old and well established is the plantation? And are conservation management goals being implemented?

Quine and Humphrey (2010) specifically consider exotic planted species and whether they facilitate or inhibit native biodiversity in Britain. Traditionally, it has been assumed that plantations of exotic conifer species have little relevance as a habitat; however, Quine and Humphrey (2010) conclude that emergent ecosystems of exotic conifer can support substantial native biodiversity, in particular where these exotic conifer species are already well established or if native woodland is scarce.

It is not just large rural forests that contribute to biodiversity and the environmental goods and services they provide; trees and woodlands located in urban areas are also important. Johnston, Nail and James (2011) discuss the debate among urban forest professionals regarding the role of exotic versus native tree species and their contribution to urban biodiversity in Britain. They assess the current evidence and conclude that an automatic preference for native species cannot be justified and that biodiversity and the wide range of services provided will be restricted by just selecting from the few native species that thrive in urban environments. Croci *et al*. (2008) suggest that effective management of urban woodlands could be a good option for promoting biodiversity in towns, and Davies *et al*. (2009) and Cameron *et al*. (2012) suggest that domestic gardens also provide an important contribution to UK biodiversity habitat and hence conservation. What is important in management and new planting decisions is a scientific understanding of the roles of particular species and the complex interactions in urban ecosystems.

(iii) Climate change impacts upon woodland and tree-related biodiversity

It has been suggested that the diversity of trees within woodlands and the variation in woodlands across landscapes enhances their resilience (here defined as the ability to withstand future shocks) and thereby maintains the provision of ecosystem services (Pascual *et al*., 2010). Nevertheless, the integrated systems characteristic of most natural habitats makes it difficult to predict the consequences of complex drivers of change such as those induced by climate change. Woodlands are no exception to this challenge. Complex biotic interactions exist, such as the competition between various species operating at different trophic levels. As such, changes to forest ecosystems resulting from climate change (and other drivers) may have poorly understood and potentially serious impacts on a range of different species of flora, fauna and fungi.

In an attempt to address this complexity a literature is developing examining the effect of climate change on the suitability of regions for certain native tree species. For example, Berry, Onishi and Paterson (2012) examine how recent changes in precipitation patterns have started to affect some species in southern Europe, such as the beech in northern Spain. Further evidence is provided by the Woodland Trust's 'Nature Calendar' survey which tracks phenological events for animals and plants in spring and autumn. These data reveal substantial increases in the growing season, for example the common oak is now producing new leaves 10 days earlier on average than in the 1980s (Woodland Trust, 2015b).

To investigate the effect of climate change on woodland tree, shrub, plant, mammal, bird and insect populations, Berry, Onishi and Paterson (2012) developed a bioclimatic envelope model. In total they studied 178 woodland species using analyses which incorporate predictions regarding changes to temperature, growing days and moisture along with species distribution data.[26] The model assesses the potential changes to the climate space for each species (the land suitable for future distributions of species governed by the climate). Berry, Onishi and Paterson (2012) conclude that different species have different responses to climate change. The authors show that some species will be 'winners' (gaining bioclimatic space) and some 'losers' (losing bioclimatic space). In particular they show that certain species in the southeast of England will lose suitable bioclimatic space due to increased water stress. However, some of the species that are currently dominant in the south of England will in the future modify their range to be more successful competitors further north.

The relative lack of diversity in the dominant canopy tree species of Great Britain may lead to exotic or introduced species becoming more competitive. These exotic species may well provide some important ecosystem functioning roles such as shade, views and timber productivity; however, whether they can provide the biodiversity conservation role of native trees is still an open question (Mace, 2013). Competitive interactions between dominant tree species are often reliant on small differences in climate, soil type or moisture. It is therefore difficult to predict if replacement of lost species will occur and if so then what species would actually be successful replacements. This is vital for understanding how the future functioning of woodland and its biodiversity supporting services would be affected by such a change.

Final environmental goods and services

The variety of interrelationships between species within an ecosystem means that the place of biodiversity within the environmental goods and services framework (Section 1) is also complex (Mace, Norris and Fitter, 2012). Woodland biodiversity delivers a range of intermediate goods and services. For example, if afforestation leads to improved soil microbial biodiversity then this in turn provides the vital underpinning for final environmental goods and services such as carbon storage and the values associated with an equable climate. Woodland also provides habitat for pollinators, the final environmental goods and services from which (pollination services) contribute to agricultural values (Smith *et al*., 2011). However, the pollination example illustrates a further important principle of the economic valuation of biodiversity. Unless those who hold values are concerned about the particular species providing a service, then they may be indifferent about changes within an ecosystem (including the structure of its biodiversity) which hold the level of service provided constant. Here then there may be substitution between species (Mace, Norris and Fitter, 2012). So, for example, in the absence of specific preferences for pollination by honeybees then a loss of bees which is accompanied by an increase in population of other pollinating insects such that services are maintained will not result in a loss in value. It is only when the particular species of pollinator itself becomes of value that its loss generates a value other than that associated with a reduction in pollinator services.

[26] Two main climate change scenarios from the Special Report on Emissions Scenarios (SRES) (A2 and B1) were used which cover much of the range of possible driving forces of future greenhouse gas emissions. These two scenarios were then used at three different time-periods (2011–2020, 2041–2050 and 2071–2080) and were derived from two global climate models (HadCM3 and PCM).

Woodland biodiversity networks also support the key individual species, such as pheasant, which are the focus of hunting and shooting sport values. Similarly, woodlands yield the habitats for specialist recreation values such as nature and bird watching (the impact of woodland upon informal visits is discussed in the section on recreation, Section 5, of this report).

All of the above final environmental goods and services are associated with use values. However, maintaining biodiversity in forests also provides non-use benefits (Pearce and Turner, 1990). These can include values associated with the knowledge that a species is safe from the threat of extinction ('existence value') and the benefits of being able to conserve species for others both now and in the future ('bequest value'). Note that these values are entirely independent of the valuer having any interaction with the species of value.

Finally, woodland biodiversity may improve an ecosystem's resilience to shocks, such as climate change, through the ability to adapt and persist into the future (Pascual *et al*., 2010).

Biodiversity quality units

Widely used biodiversity indicators include:

- number of species
- distribution of species
- DNA genetic difference based measures of ecological diversity (Purvis and Hector, 2000)
- abundance and population distribution

A more encompassing definition of biodiversity, such as that given by the Convention on Biological Diversity,[27] would consider the diversity of the natural environment including species alongside habitat and ecosystem diversity. However, the empirical tractability of any definition is a key issue and metrics for rapid and effective assessment biodiversity are a recognised requirement with techniques such as eDNA sampling being the subject of considerable ongoing research.[28]

As discussed above, individual or groups of species are frequently used as indicators for wider biodiversity. Conceptually such approaches still address the valuation of biodiversity. However, studies of iconic species refer only to those particular species (even where, as outlined above, the conservation of wider biodiversity is a prerequisite for the conservation of the iconic species). Studies of iconic species rather than general biodiversity may well provide a better reflection of most people's preferences regarding wildlife.

Economic production functions

Woodland and tree-related biodiversity enters the following economic production functions:

- Agricultural production – through improving soil fertility and delivering pollination services
- Direct food production – through forest foods such as fungi and berries
- Sport (hunting) – by supporting species which are hunted
- Physical health – there is recent evidence to suggest that certain microbes associated with greenspace and woodlands may enhance human immunity systems and hence promote health (Sandifer, Sutton-Grier and Ward, 2015)
- Nature watching – a substantial number of people derive benefits from observing wild species (most prominently birds)
- Recreation – biodiversity supports species appreciated in general recreation
- Artistic – as an input to or inspiration for the production of art by amateur and professional artists
- Learning – opportunities for educators, students and researchers to learn from and experience the environment
- Spiritual and cultural – for spiritual, ceremonial or celebratory purposes
- Non-use value – the benefits trees provide for people who care about existence value of the environment (those who think it is important to preserve the environment for moral/ethical connection or fear of unintended consequences) or bequest values (those who think it is important to preserve the environment for future generations)

Beneficiaries

The variety of production functions supported by biodiversity results in a variety of beneficiaries. Farmers benefit from the enhancements to agriculture which biodiversity brings through improving soil fertility and delivering pollination services. Recreationalists benefit both from the enjoyment provided by visits and from health enhancements. Specialist recreationalists such as hunters or those engaged in nature and bird watching also benefit from woodlands. Other users include artists, educators, students and those obtaining spiritual and cultural benefits. Furthermore, it seems likely that a substantial proportion of the population derive non-use values from the conservation of biodiverse habitats such as woodlands.

[27] http://www.biodiv.org/
[28] NERC has recently announced the funding of research into the use of eDNA techniques, see http://www.nerc.ac.uk/latest/news/nerc/highlight-topic/

Valuation methods

A number of valuation methods have been applied in the area of biodiversity, including:

- Pollination and fertility services to agriculture can be assessed through production function methods (see Annex 1).
- Health enhancements derived from a more biodiverse microbial environment can in theory be assessed through the health valuation methods reviewed elsewhere in this report. However, this requires more accurate and quantified assessment of the physical pathways from woodland biodiversity to health effects than is currently available.
- Sporting values are amenable to assessment via market prices for shooting and the purchase of land with shooting rights.
- Both general and wildlife-orientated recreation should be amenable to valuation via revealed preference (e.g. travel cost) methods.
- Non-use values can only be directly assessed via stated preference methods although some recent studies have examined the use of cost-based approaches to delivering set standards (e.g. no-loss) for biodiversity. However, the latter costs cannot be taken as being estimates of non-use value benefits.

Valuation scale

Valuation studies have been conducted from the very local scale of small woodlands right up to national scale.

Valuation estimates

The Woodland Valuation Tool currently contains 48 valuation studies or reviews and 36 references to woodland biophysical studies relating to biodiversity (in flora, fauna and the environment). The valuation literature ranges from studies of use values such as pollination to non-use (existence and bequest) values.

Use values

Pollination

Forests act as reservoirs of insects that perform pollination and seed dispersal functions, both within the forest and the wider environment.

The UK National Ecosystem Assessment (2011) uses the methods set out in Gallai *et al*. (2009)[29] and reported that the contribution of insect pollination to the crop market was GBP 430 million (in 2007 GBP). In another study Breeze *et al*. (2011) reported a value equal to GBP 1058 million (in 2007 GBP) with insect pollination covering 20.4% of total UK cropland. Regionally, southeast England has the greatest area of insect-pollinated crops, occupying approximately 30% of cropland, due in major part to the large areas of fruit growing within the region. In contrast, southwest Scotland has the smallest proportion of pollinated crops at about 2%. Breeze *et al*. (2011) used national-level data for all food and non-food crops reported in the 'Agriculture in the UK report' (Defra, 2010). The total crop market value is calculated using 2007 farm gate price (the price of produce sold from the farm). It is important to note that the value presented should not be interpreted as the value that might be lost if insect pollination ceased; this is because even in the absence of insect pollination some production would still occur through wind pollination. In addition, although tree and forest environments act as reservoirs for pollinating insects, other environments (e.g. meadows, grassland, moors and heathland and domestic gardens) can also provide those services. As such trees and forests should only be assigned a proportion of the total value, and the specific proportion is an ecological question regarding the contribution of woodlands to the overall supporting services of pollinating insects.

Of course some trees are themselves highly dependent upon biodiversity-based pollination. This is particularly true for fruit trees where insect pollination can directly influence yields. Garratt *et al*. (2014) conducted field experiments on apple orchards in Kent and found that insect pollination of both Gala and Cox apples resulted in greater yields than wind pollination alone. This was estimated to be worth an additional GBP 11 900 in output per hectare for Cox and GBP 14 800 per hectare for Gala apples, compared with wind pollination. Output is valued at 2013 farm gate prices, and takes into account changes in both quantity and quality of apples produced. The value is likely to overstate pollination benefits, as increases in other inputs may also achieve an increase in yields.

Non-timber forest products

Non-timber forest products such as fruit, nuts and fungi are harvested every year from forests both commercially and non-commercially. As part of the UK NEA, Valatin and Starling (2010) review the available evidence and find that deer contribute around GBP 12 million gross value added to the Scottish economy, and directly or indirectly supports over 2000 full-time equivalent jobs. It should be noted that this includes the value for recreation hunting, in addition to the value of the venison meat with recreational hunting making up the majority of that value. Valatin and Starling (2010) also note the negative impact of deer on timber production from the stripping of bark from trees. Ward *et al*.

[29] Gallai *et al*. (2009) estimated that insect pollinators were directly responsible for 9.5% (around EUR 153 billion) of the total value of the world's agricultural food production.

(2004) provide an estimate of the cost of bark stripping by deer at around GBP 60 per hectare per year (in 2004 GBP) for softwood. Apportioning the costs and benefits of non-forest products is complicated by the fact that these products may be supported by several habitats; for example, deer may spend only part of their time in woodlands. The concept of additionality suggests that the value attributed to woodlands should be the additional benefits provided by the presence of the woodland in addition to the alternative habitat (Valatin, 2012).

Both the costs and benefits of non-timber forest products have so far received relatively little research in Britain; however, internationally there has been a more concerted effort to value non-timber forest products. For example, in Tanzania, Schaafsma *et al*. (2012, 2014) show that the total benefit flow of charcoal, firewood, poles and thatch to the local population has an estimated value of USD 42 million per year (in 2010 USD), providing an important source of additional income for the poorest local communities.

Recreation

The direct appreciation of wildlife can generate substantial recreational benefits. The use values of participation in activities such as bird watching and nature viewing are considered in the recreation section (Section 5) of this report.

Non-use values

The non-use value from biodiversity is the value humans assign to the continued existence of species or habitats; for example, the benefit an individual derives from knowing that a species exists even if they are unlikely to see it (existence value) or from being able to pass such benefits to other people or future generations (bequest value). Unlike use values we cannot observe people's behaviour regarding non-use values. Because of this some have proposed that we can calculate partial or lower bound estimates of non-use values from agri-environmental scheme payments (e.g. the woodland capital grants under Countryside Stewardship), or legacy payments to environmental charities (Morling *et al*., 2010, Mourato *et al*., 2010). However, such approaches lack theoretical justification as they rely upon very strong assumptions regarding decision-makers' knowledge of the impacts of intervention and their ability to interpret social preferences. Given this, the academic literature has favoured the application of stated preference techniques as the principle method used to assess the non-use value of biodiversity. This literature is briefly reviewed (and subsequently critiqued) below.

Stated preference willingness to pay values underpin the non-use valuation estimates reported in Hanley *et al*. (2002) and Willis *et al*. (2003). Rather than undertake a primary valuation exercise Hanley *et al*. (2002) utilise the earlier analysis by Garrod and Willis (1997) on remote upland coniferous forests in Britain to generalise across other forests types. The Garrod and Willis study asks a representative sample of 650 households across Great Britain a contingent ranking question to elicit the value of marginal changes in biodiversity in remote upland coniferous forests. The value for increasing biodiversity of these forests at the margin was approximately GBP 0.35 per household per year for 12 000 ha of coniferous plantations to be brought into good management through restructuring. Hanley *et al*. (2002), using seven general public focus groups and one expert focus group (each of eight people), extended the Garrod and Willis (1997) results to other types of forests with values ranging from GBP 0.33 for lowland coniferous forests to GBP 1.13 for lowland ancient semi-natural broadleaved forest per household per year for 12 000 ha of conservation.

Although specific to the non-use benefits of UK woodland biodiversity, the Garrod and Willis (1997), Hanley *et al*. (2002) and Willis *et al*. (2003) valuation estimates have a number of limitations. The primary research underpinning the study has a sample size of just 650 households to cover the entirety of Great Britain. Furthermore, as the sampling for this research was conducted over 20 years ago (in 1995) the potential for changes in preferences also arises. Valuation techniques have also advanced significantly. For example, the original study failed to consider the impact of scale upon values. So it is possible, indeed likely, that non-use values for biodiversity are not linearly related to the area of habitat conserved (or even to the population size protected).[30] Simple linear extrapolation of results is likely to generate relatively high value estimates which cannot readily be defended in the absence of specific investigation. Such knowledge gaps constitute a significant research challenge for the literature and for decision-making.

Presenting biodiversity in a way that is understandable to the respondents of stated preference surveys is a further challenge to researchers. Biodiversity often encompasses a variety of attributes and as such the relevant measure varies with the aim of the valuation study. Sometimes the relevant measure is the conservation of a single species, while at other times the relevant measure is species richness or the percentage change in habitat. In a literature review of biodiversity related choice experiments, Bakhtiari *et al*. (2014) find that 50 of 55 studies describe the

[30] It is worth noting that, given the 26.7 million households in the UK at present, the Garrod and Willis estimates imply an annual value of over GBP 9 million for a 12 000 ha woodland or nearly GBP 800 per hectare per year.

complexities of biodiversity using simple measures such as the number of species. In contrast both Christie *et al*. (2006a) and Czajkowski, Buszko-Briggs and Hanley (2009) attempt to value biodiversity using multiple attributes to describe some of the complexity of biodiversity. Christie *et al*. (2006a) applied both choice experiment and contingent valuation methods in order to value the diversity of biological diversity on English agricultural land. Two samples were collected, one in Cambridgeshire and one in Northumberland, with the samples asked to value changes to their local region (changes that will enhance biodiversity in Cambridgeshire for those sampled in Cambridgeshire and Northumberland for those sampled in Northumberland). Within the contingent valuation study, Christie *et al*. (2006a) examined willingness to pay for three biodiversity enhancements: (i) an agri-environmental scheme incorporating conservation aims such as reducing pesticide use, (ii) habitat creation and (iii) protecting land under agri-environmental schemes from conversion to housing developments. The results of the contingent valuation study, pooled across all three biodiversity enhancements, reveal mean willingness to pay values of GBP 58.87 per household per year for the Cambridgeshire sample (95% confidence interval GBP 47.38–70.36) and GBP 42.47 per household per year for the Northumberland sample (95% confidence interval GBP 34.67–50.27) based on an annual tax increase for the next five years (in 2004 GBP).

The choice experiment reported in Christie *et al*. (2006a) initially used focus groups to identify ecological components of biodiversity that were both important and relevant to the general public. These findings were subsequently used to design a choice experiment that included a range of attributes including familiarity of species, species rarity, habitat and restoration of ecosystem processes. The results are presented in Table 7.1. The results can be interpreted as average increases in household utility annually for the next five years, so in the Cambridgeshire sample for example, the value of moving from the current state of 'continued decline of familiar species' to the protection of 'rare familiar species' or the protection of 'rare and common familiar species' increases utility by GBP 35.65 or GBP 93.49 per household per year, respectively. Overall the results show high positive valuation preferences for most components of biodiversity (the exception is slowing the decline of rare, unfamiliar species).

Czajkowski, Buszko-Briggs and Hanley (2009) apply a similar method to the choice experiment in Christie *et al*. (2006a) but apply it specifically to value non-use benefits of biodiversity in forests in Poland. The biodiversity attributes they study include structural, species and functional diversity, thus extending the list of biodiversity attributes considered by Christie *et al*. (2006), while introducing ideas of structural, species and functional diversity. The results are presented in Table 7.2 and are for

Table 7.1 Choice experiment results from Christie *et al*. (2006a) – non-use values of biodiversity in England*.

Baseline comparison	Variable	Implicit price per household per year (2004 GBP) Cambridgeshire	Implicit price per household per year (2004 GBP) Northumberland
Continued decline in population of familiar species	Protect rare familiar species from decline	35.65	90.59
Continued decline in population of familiar species	Protect both common and rare familiar species from decline	93.49	97.71
Continued decline in population of rare species	Slow the decline of rare, unfamiliar species	-46.68**	n/a
Continued decline in population of rare species	Stop the decline of rare, unfamiliar species	115.13	189.05
Continued degradation and loss of habitat	Restore habitat quality through better management	34.40	71.15
Continued degradation and loss of habitat	Re-create new habitat areas	61.36	74.00
Continued decline of ecosystem functioning	Restore only ecosystem services that directly impact humans	53.62	105.22
Continued decline of ecosystem functioning	Restore all ecosystem services	42.21	n/a

* All values are statistically significant where reported.
** The findings for the slowing the decline attribute level were reported to be negative in the Cambridgeshire sample (indicating that negative utility would be gained from a slowdown in the decline of the population of rare unfamiliar species). Therefore it appears that the public is unwilling to support policies that simply delay the time it takes for such species to become locally extinct.

Table 7.2 Choice experiment results from Czajkowski, Buszko-Briggs and Hanley (2009) – non-use values of forest biodiversity in Poland.

Variable	Baseline comparison	Implicit price per household per year (2007 euros)
Rare species (maintain and improve current populations)	A decline threatening total extinction of some species	3.12
30% of total area under passive protection	Passive protection of 16% of total forest area (current level)	4.32
60% of total area under passive protection	Passive protection of 16% of total forest area (current level)	5.52
10% of total area under active protection	Absence of some biotopes and ecological niches and a decrease in quality of others	3.98
30% of total area under active protection	Absence of some biotopes and ecological niches and a decrease in quality of others	4.21
60% of total area under active protection	Absence of some biotopes and ecological niches and a decrease in quality of others	5.60

an annual tax increase for the next 10 years in 2007 euros. Although the attributes vary between the studies it is clear that the amounts are much smaller in Czajkowski, Buszko-Briggs and Hanley (2009) (ranging from EUR 3.12 to EUR 5.60) than those in Christie *et al*. (2006a) (ranging from GBP -46.68 to GBP 189.05). Czajkowski, Buszko-Briggs and Hanley (2009) offer some justification for these differences by highlighting the differences in approach, attributes, context and location between the studies but this stark difference also shows the inherent difficultly in deriving non-use values for the benefits of biodiversity in a consistent and meaningful way

Research gaps

While stated preference methods are in theory applicable to the valuation of the non-use benefits of biodiversity, there is a common absence of critical validation characterising much of the stated preference literature regarding biodiversity non-use valuation. So studies have failed to assess basic issues such as whether and to what extent values are responsive to changes in the definition of the good (i.e. biodiversity) on offer? For example, are stated preference values responsive to changes in the magnitude (the 'scope') of goods? Similarly, do stated preference values for biodiversity change as we vary the distance between the valuing individual and the biodiversity change?

A significant complication here is the lack of clear prior expectations for such tests with respect to non-use values (Bateman, 2011). For use values we expect that increasing distance to a good will lower willingness to pay. That is not necessarily the case with non-use goods – as they are not used and so distance might be thought of as irrelevant. Actually the little evidence that is available (from non-woodland contexts) suggests that distance decay also applies to non-use values.

The relationship with the size (scope) of a non-use good is also a priori unclear. So people may be concerned to ensure that a population is maintained above a resilience threshold, but may (or may not) be indifferent to further increases in population size. People may also care about assemblages of species or simply a single iconic species. These are key questions which remain substantively unanswered.

Stated preference studies of biodiversity also face significant problems because of a lack of familiarity with the good under investigation. People typically do not understand the concept of biodiversity. This means that the analyst is more than usually reliant upon the provision of information, much of which is potentially challenging for the respondent. While recent advances in the visualisation of stated preference information have been shown to significantly reduce anomalous responses (Bateman *et al*., 2009), nevertheless, strong reliance upon unfamiliar information makes stated preference studies prone to the problem of preference construction (Lichtenstein and Slovic, 2006), where the framing of questions significantly influences survey responses.

Concerns regarding preference construction in stated preference studies of non-use values are important given evidence that respondents in such surveys can find it difficult to provide answers to choice questions (Christie and Gibbons, 2011). The majority of valuation studies in this field have reacted to this challenge by focusing upon iconic species rather than biodiversity (Bakhtiari *et al*., 2014). Some commentators have argued that such approaches will tend to lead to higher value estimates (Jacobsen *et al*., 2008) although this is not necessarily a sign of poor validity (i.e.

values for iconic species preservation may indeed be substantial). A more fundamental issue is whether the values and preferences that individuals hold conform to what is ecologically feasible or sustainable (Atkinson, Bateman and Mourato, 2012; Morse-Jones *et al*., 2012).

Given the lack of clear theoretical or even empirical expectations regarding the nature of valid preferences, combined with the technical problems of valid preference elicitation and the issue of whether preferences align with ecological feasibility, some analysts have argued against the use of stated presence valuation of non-use biodiversity values (Bateman, Mace *et al*., 2011). In a recent application Bateman, Harwood *et al*. (2013) conduct an environmental–economic analysis of various scenarios of land-use change in which non-use biodiversity is not valued but is instead treated as a constraint upon an optimisation analysis. In the latter application a 'no-loss' constraint was applied wherein, for a study of the entirety of Great Britain if any proposed land-use change generated a reduction in biodiversity within a 2 km × 2 km grid cell, then that change was not implemented for that cell and alternative land-use options were adopted (note that a binding constraint in one cell was not allowed to prevent a change occurring in other cells, thereby ensuring that otherwise efficient policy changes where not generally prohibited). Such an approach yields a minimum cost solution for ensuring no-loss outcomes for biodiversity. Further investigation of such opportunity cost approaches appears well worthwhile given the complexities of stated preference estimation of non-use values; however, it should be noted that opportunity costs are not estimates of economic value.

The above review highlights two very clear research gaps:

- The valuation of biodiversity, both use values and (especially) non-use values, remains a very significant gap in the research literature. Both stated preference and constrained optimisation approaches have only had cursory application. Given the biophysical relationships between woodland and biodiversity it seems likely that the latter values are substantial. As such this identifies a clear priority for future research.
- The need for improvements in the economic valuation of biodiversity needs to be. matched by better data and natural science understanding of the physical impacts of afforestation upon measures of biodiversity. As mentioned previously, in both the UK NEA and UK NEAFO analyses biodiversity was assessed through indices of various indicator bird species (Hulme and Siriwardena, 2011; Bateman, Harwood *et al*., 2013, 2014). This approach was adopted due to the relatively poor cross-sectional and time-series data available for wider measures of biodiversity; a factor which marks out a significant research gap for future assessments. Similarly, understanding of the relationships between woodland biodiversity and human health requires more accurate and quantified assessment of the underpinning physical pathways of effect than is currently available.

8. Trees and woodlands on farms

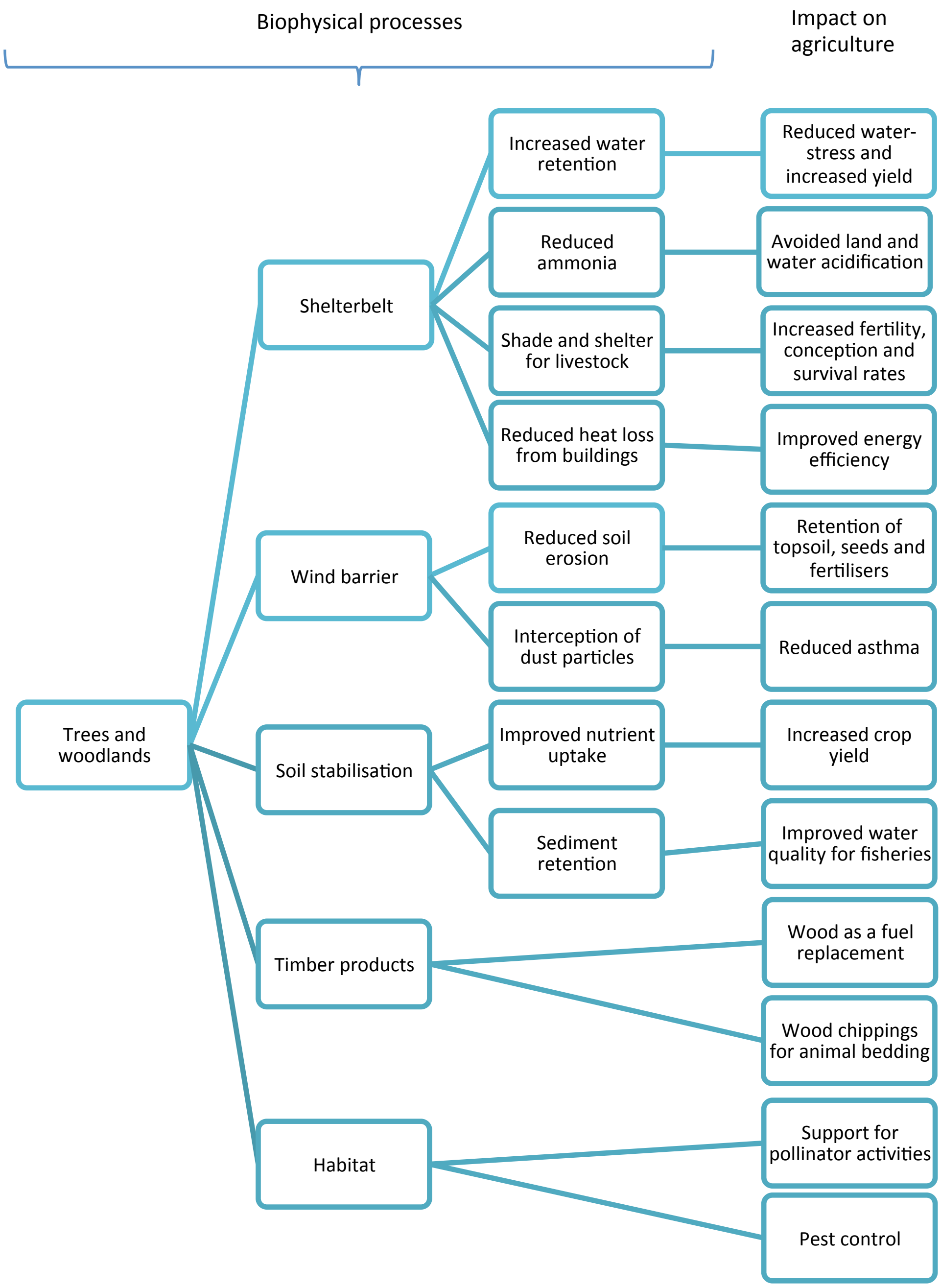
Biophysical pathways

Trees and woodlands provide a number of benefits to arable and livestock farms through numerous biophysical pathways (Figure 8.1). These benefits can be grouped under those resulting from the trees or woodland (i) providing a shelterbelt, (ii) acting as a wind barrier, (iii) stabilising soil, (iv) providing wood for fuel and bedding and (v) influencing crop pollination or reducing the prevalence of pests.

(i) Providing a shelterbelt

- Drought and water conservation: Water loss from crops through transpiration and loss of soil moisture leads to water-stressed crops and reduces crop yields. Shelterbelts provided by trees lower wind speeds, increase humidity and reduce loss through evapotranspiration. Although trees create shade and compete for water and nutrients, leading to a loss of yield around the shelterbelt, the protection provided to the remaining field typically exceeds this loss. Shelterbelts with optimal porosity can

Figure 8.1 Biophysical pathways associated with trees and woodlands on farms.



protect an area of up to 30 times their height. In particular, studies have shown that shelterbelts can increase wheat and barley yields in the UK (Hough and Cooper, 1988), Italy (Campi, Palumbo and Mastrorilli, 2009) and Canada. The benefits of shelterbelts are increased when the plants are water stressed and wind direction is consistent. This is increasingly important in the light of predictions that climate change will lead to warmer and drier climates in the southeast of the UK.

- Ammonia: Emissions from livestock can damage some plant species and lead to acidification of land and water. Buffering important habitats by planting native trees in the path of emissions from livestock units can reduce the impact. Applied studies have shown that shelterbelts next to livestock units can reduce ammonia emissions by up to 10% (Woodland Trust, 2012), while recent modelling studies, accounting for optimal tree canopy structures, predict ammonia capture rates of 3–46% depending on livestock type and management system (Bealey *et al*., 2007).
- Shelter and shade for livestock: Farm animals are vulnerable to increased temperatures and, for outdoor poultry and livestock, solar radiation; this affects feed intake, reproductive performance and susceptibility to disease. Shade from trees can protect livestock against extreme temperatures, increasing ewe conception rates and ram fertility, as well as protecting against cold, reducing feed intake and increasing survival rates for lambs (Woodland Trust, 2012).
- Reduced heating costs for farm buildings: Trees can reduce heat loss from buildings in the winter and provide shade in summer, reducing heating costs by between 5 and 40% depending on the insulation (Woodland Trust, 2012).

(ii) Acting as a wind barrier

- Wind erosion can lead to a loss of topsoil, seeds, fertilisers and agrochemicals. Fine seedbeds for sugar beet, carrots and onions are more prone to erosion; this is particularly relevant for Yorkshire, the East Midlands and East Anglia (Woodland Trust, 2015a).
- Trees act as a barrier for dust created by dry weather and wind. This can reduce the incidence of asthma and improve the health of farm staff.

(iii) Stabilising soil

Trees can help reduce soil and water movement by increasing water infiltration rates and slowing the flow of transported sediments. This increases nutrient uptake from the soil and reduces phosphate and pollutant runoff through sediment control (Woodland Trust, 2013). Sediment deposits can increase the turbidity of water bodies and settle in spawning beds, thereby affecting valuable fisheries.

(iv) Providing wood for fuel and bedding

Trees can be grown in areas that are unsuitable for crops. Wood fuel can then be used in place of other fuels and wood chippings can be used as an alternative to straw for animal bedding (Woodland Trust, 2012).

(v) Crop pollination and pests

Trees provide habitat and shelter for pollinator activity. Moreover, it has been shown that trees can reduce the prevalence of crop pests by providing non-crop habitat (Woodland Trust, 2015a).

Agriculture units

The economic value of agriculture is often measured using market prices to calculate farm profit. When profit information is unavailable agricultural value has been estimated using farm gross margins, crop yield, crop value (GBP per hectare) and livestock head counts.

Economic production functions

Agriculture enters a number of production functions:

- Food – agricultural output is processed, packaged and sold by the food industry
- Recreation – as a landscape amenity value
- Health – agricultural production contributes to air pollution and water pollution which adversely affect physical health. Agriculture also provides a visual amenity which could contribute to mental health
- Housing – as a landscape amenity
- Spiritual and cultural experiences – agricultural heritage and the culture of farming practices are inputs to spiritual and cultural experiences. Farmers are often seen as fulfilling a traditional role as custodians of the environment
- Non-use – the benefits for people who care about existence value of agricultural practices (those who think it is important to protect cultural farming practices or the environment via agricultural stewardship) or bequest values (those who think it is important to preserve agricultural practices for future generations). Agriculture also provides non-use values supporting genetic value (e.g. diversity in genetic resources for future production, and the conservation of rare breeds of livestock)

Beneficiaries

Agriculture provides benefits to farmers through farm incomes, to industrial producers through the provision of agricultural outputs as inputs to production, and to the general public through amenity value and indirectly through the provision of food.

Valuation methods

The existing evidence base provides very few valuation studies that examine the value of trees and woodlands in terms of agriculture. Bateman *et al*. (1996) provide an estimate of farmers' willingness to accept compensation in return for establishing a recreational woodland, which would displace existing farm activities. This study captures the fact that the establishment of a woodland designed for recreation is likely to be costly and reduce farm income from other land uses. However, the study was not designed to capture the benefits to farmers of the multitude of services provided by strategic planting of trees on the farm (as outlined earlier in this section).

Willis *et al*. (2003) estimate the cost of water lost to trees and woodlands that would have been abstracted at GBP (2001) 0.13–1.24 per cubic metre; however, this value is based on the assumption that for every cubic metre of water taken up by trees none of this can be abstracted. The authors are clear that this is an assumption made due to a lack of biophysical information.

If the biophysical processes were fully understood it would be possible to multiply the impact of trees and woodlands on agricultural outputs by the relevant market prices. However, information on individual farm scale benefits is limited. Although the biophysical evidence is building this is still very generalised and likely to be farm specific with contextual attributes such as wind direction and the aspect, altitude and slope of the land playing a significant role in determining the magnitude of the benefits provided by on-farm trees.

Valuation scale

Stated preference and market-based valuation methods tend to operate at the individual farm level.

Valuation estimates

The Woodland Valuation Tool currently contains 3 valuation studies and 4 biophysical studies relating to agriculture.

Bateman *et al*. (1996) report a mean for a farmer's willingness to accept compensation of GBP 300 per hectare (1991 GBP) to establish a recreational woodland in place of existing land use.

Research gaps

- There are gaps in understanding the biophysical links between trees and woodlands and agricultural output, in particular spatial and temporal differences as well as the relative merits of different species and management practices. For example:
  - Understanding the importance of the species, age and location of trees on farms for the provision of soil stabilisation, particularly in the context of an increase in the frequency of extreme weather events due to climate change.
  - Research on the importance of habitat configuration and connectivity to support biodiversity, and conversely to reduce risks from pests.
  - A deeper understanding of the relationship between different species and management practices, different pollinators and their combined impact on agricultural yields.

9. Plant (tree) health

Plant health is a notoriously ill-defined and yet commonly used term, as is discussed by Döring *et al*. (2012) who open their article by posing the questions: What is 'plant health'? How can we know when a plant is healthy? What are the criteria to assess health in plants?

In this section we consider the impact of tree health on the value of benefits provided by trees and woodlands. In particular, we interpret the term 'tree health' as encompassing a number of characteristics of the tree such as (i) whether the tree is suffering from pest infestation or tree diseases and (ii) the physical condition of the tree including canopy size, age and structural integrity. The relationships between trees and woodlands and crop health are addressed separately in Section 8 on agriculture.

As is depicted in Figure 9.1, the incidence of tree disease in Great Britain has been rising rapidly and it is anticipated to rise further under pressure from cross-border trade, climate change and human spread of invasive species (NCC, 2014).

Uses

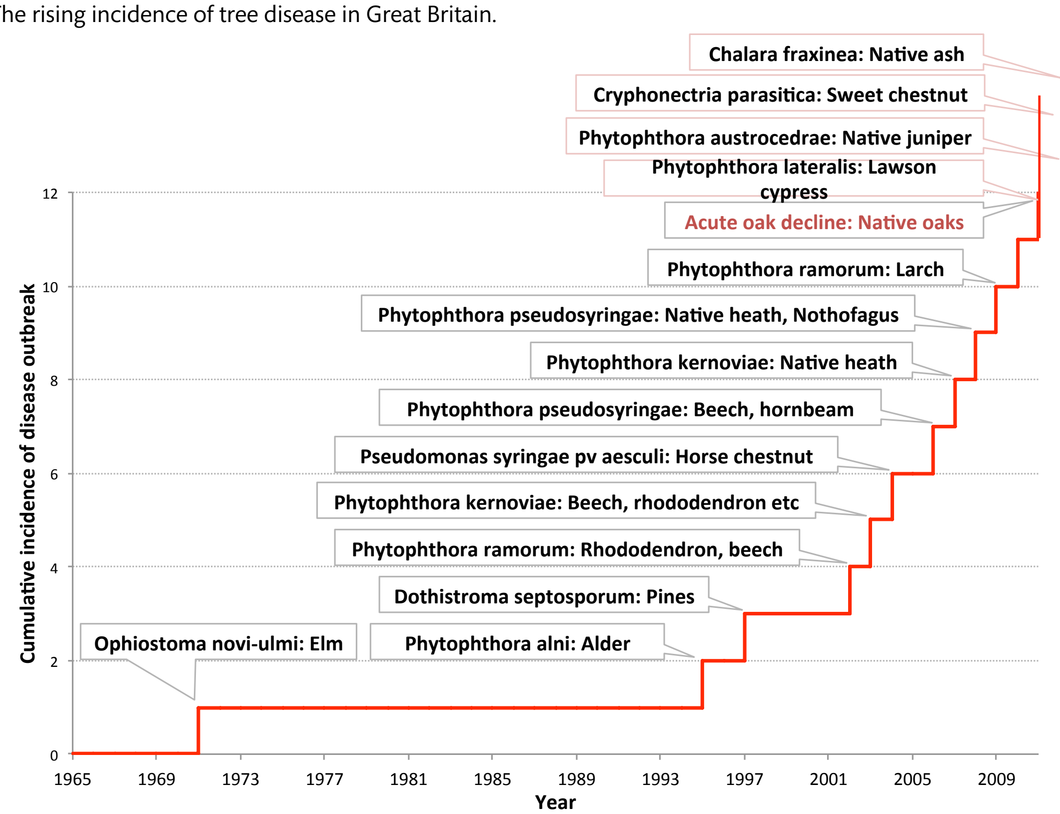
Information on tree health and its impact on the economic value of the social and environmental benefits provided by trees and woodlands is important for a number of decision-making purposes including:

- investment and management decisions for existing and new woodlands
- assessing the economic justification for disease control measures
- making decisions on the removal of trees
- scaling broader valuation numbers to account for changes in biophysical functioning of diseased trees and woodlands
- communicating risks associated with tree health

The impact of tree health on value

The impacts of pest and disease regulation on biophysical processes and economic values are very broad: most obviously, tree health can affect timber yield. This affects economic values by reducing the quantity of timber available to turn into marketable products. However, this is only one of many damage costs that could and should be accounted for when considering the benefits (or costs) of pest and disease regulations. Additional costs include potential knock-on reductions in agricultural and horticultural yields that occur when pests and diseases

Figure 9.1 The rising incidence of tree disease in Great Britain.



Source: Forest Research and C. Reid, personal communication as referenced in the NCC State of natural capital report (NCC, 2014).

hinder the regulatory functions provided by trees and woodlands, including pollination and habitat provision for both crop promoting and crop destroying species (e.g. rabbits, snails, birds and some insect pests (Bebber, Ramotowski and Gurr, 2013; Hanula, Horn and O'Brien, 2015)). Tree health also affects the quantity of carbon storage provided by trees and the carbon emissions that should be attributed to timber products that can be made from the resulting quality grade of timber.

More generally, pests and diseases can be seen as a factor affecting the quality of trees and woodlands and the environmental goods and services provided by them. This notion is reflected in the approach taken by decision-making tools such as i-Tree, CAVAT and Helliwell (see Section 10 on Urban trees for further details), which all scale their benefit values using an expertly judged or surveyed measure of tree health (e.g. life expectancy, canopy size and trunk diameter). From an ecosystem services paradigm approach, tree health can be considered as a factor affecting (i) the biophysical functioning of trees and their provision of clean water, clean air, carbon storage and habitat for wildlife and (ii) the value derived from trees and woodlands as recreational amenities, visual amenities (views), as inputs to artistic production, learning experiences, spiritual and cultural experiences, and non-use values associated with trees and woodlands.

Changes in tree health create gains and losses in both the quantity and quality of trees and woodlands. This presents empirical and methodological challenges. From an empirical standpoint, the valuation of incomplete gains (losses) often requires sophisticated adjustment from a literature which is dominated by valuations of complete changes from one state to another. Methodologically a mixture of gains and losses, while being straightforward from a standard economic theory perspective, can trigger psychological phenomena, which challenge economic theory by noting a disproportionate reaction to losses in comparison to gains. These issues are considered in further detail in Section 11 using plant health as a motivating example.

Economic values

Pests and diseases were included in the Eftec (2011) scoping study; however, the existing evidence at the time was very limited and thus the details provided were minimal. The report concludes that while the pest and disease regulation role of forests and woodlands can give rise to economic values in terms of avoided damage costs (e.g. to agricultural and horticultural enterprises), the empirical evidence to this effect is lacking. Since the publication of the Eftec (2011) report, there has been a movement towards understanding the broader implications of plant health, beyond reductions in yield. This has been accompanied by new evidence and the establishment of projects aiming to survey the broader social and cultural impacts. However, the evidence base on the magnitude of these impacts is small but emerging slowly and there is still a lot of research needed in this area; this is partly due to the difficulty of understanding the counterfactual – what would have happened if the trees had remained healthy/uninfested. Furthermore, challenges related to valuing gains and losses (see Section 11) are particularly salient when considering pest and disease related issues.

The existing evidence includes Donovan *et al*. (2013, 2015) who, using the spread of ash borer in the Midwest as a natural experiment, provide an investigation of the relationship between the spread of ash borer and the incidence of cardiovascular disease at county level and among women, respectively. Donovan *et al*. (2013) found that infested counties had increased rates of cardiovascular and lower-respiratory mortality, and that this relationship was increasing as the infestation progressed. Likewise, Donovan *et al*. (2015) conclude that, after controlling for other factors, women living in counties infested with emerald ash borer had a 25% higher risk of cardiovascular disease. It is hypothesised that these impacts are driven by increased stress, lack of physical activity and reduced air quality.

An ongoing 'societal and cultural values of trees' study by the University of York and the Stockholm Environment Institute, led by Alison Dyke, aims to develop an understanding of the wider impacts that pests and diseases have on the social and cultural values that people associate with trees, and how these values are influenced by people's knowledge of pests and diseases.[31] Although current estimates of the broader cultural and societal values associated with tree health are not yet available, it is clear that using information on damage costs, limited to timber and agriculture yields, would severely underestimate the benefits of disease prevention and remediation schemes. This is of particular concern given the existing empirical evidence on plant health (Areal and MacLoed, 2007; MacLeod, 2007), whose case studies illustrate a number of plant disease prevention schemes that are not economically viable according to cost-benefit analyses based solely on foregone yield and scheme management costs.

Holmes and Smith (2007) discuss the potential for benefit transfer in the context of sudden oak death in the USA, highlighting the challenges presented by the need to

[31] https://www.york.ac.uk/sei/researchhighlights/socialandculturalvaluesoftrees/

establish data and understand biophysical relationships at an appropriate scale and resolution, which can then be combined with GIS and benefit transfer techniques to estimate values for other areas. These sorts of benefit transfer exercises will profit from input from new resources such as the development of the UK Plant Health Risk Register and studies like Botham *et al*. (2009), which investigates the spatial and temporal relationship between land use and the distribution of non-native species in Britain.

Research gaps

The evidence base on the impact of tree health on the value of the benefits provided by trees and woodlands is small but emerging. There remains a substantial need for research in this area, in particular to address difficulties in understanding the counterfactual – what would have happened if the trees were healthy?

10. Urban trees

It is not just large rural forests that contribute to biodiversity and the environmental goods and services they provide; trees and woodlands located in urban areas are also important. Urban trees and woodlands deliver all of the same types of benefits (and costs) as rural forests (as discussed in Sections 2–9), however their location, proximity to people, differing density and position in a mosaic of different land uses can alter the value of the benefits that they provide.

Urban trees are part of a broader classification of urban ecosystems – green infrastructure. Green infrastructure includes individual street trees, hedges, grasslands, woodlands, wetlands, ponds, grass verges, gardens and parks, green walls, green roofs, rivers and canals and areas created for urban drainage (Eftec, 2013). For the purpose of this study we focus on urban trees and woodlands; this includes trees in urban forests and woodlands, publicly managed trees such as street trees and trees on private land (e.g. in domestic gardens).

Only a small segment (15%, or 21 of 140 studies) of the literature reviewed under the scoping study relates specifically to urban trees.

What distinguishes urban trees from non-urban trees and woodlands?

Urban trees are differentiated from peri-urban and rural trees and woodlands by their location and the fact they are often planted in small numbers. These two factors have important implications for understanding both the biophysical functioning and processes associated with the trees and the value of the social and environmental benefits provided by them:

- Biophysical processes: The scale of many of the existing studies is often coarse and in some cases completely neglects smaller woodlands (e.g. Powe and Willis (2002) omit woodlands smaller than 2 ha in size). Furthermore, the ambient levels of pollution in urban areas differ from those in suburban and rural areas. This can have a significant impact on biophysical processes; for example the proportion of gaseous pollutants absorbed by trees depends on a number of factors, including the pollutant concentration levels in the atmosphere (Freer-Smith and Broadmeadow, 1996).
- Economic value: The marginal value of an improvement in quality is not likely to be fixed or linear; it matters what the original level of quality is. A small improvement in air quality may be of little value if the air is already considered to be of good quality; however, it may be very valuable if the current air quality is low, particularly if a small improvement would bring the quality up to an acceptable standard (e.g. to meet a regulatory minimum).

Biophysical processes

Urban trees provide a number of environmental and social benefits. For example they:

- contribute to water resources by intercepting rainwater (Rogers, Jaluzot and Neilan, 2012; Rumble *et al*., 2014, 2015)
- influence air quality by providing air filtration (Bolund and Hunhammar, 1999; Rogers, Jaluzot and Neilan, 2012)
- contribute to climate change adaptation and mitigation through regulating micro-climates
- provide carbon storage (Rogers, Jaluzot and Neilan, 2012; Rumble *et al*., 2014, 2015)
- provide urban greenspace (Sarajevs, 2011) for recreation as well as social and cultural experiences
- reduce noise pollution (Bolund and Hunhammar, 1999)
- play an important role in sustainable communities through providing aesthetic, social and health benefits (Britt and Johnson, 2008)

They are also important for biodiversity. Croci *et al*. (2008) suggest that effective management of urban woodlands could be a good option for promoting biodiversity in towns, and Davies *et al*. (2009) and Cameron *et al*. (2012) suggest that domestic gardens also provide an important contribution to UK biodiversity habitat and hence conservation.

Valuation methods

Sections 2–9 provided a review of the general evidence for the benefits of trees and woodlands and significant gaps in the evidence base. This section will focus on the tools available for valuing urban trees and limitations in applying the existing evidence base specifically to valuing the social and environmental benefits provided by urban trees and woodlands. A summary of the tools is provided in Table 10.1.

i-Tree

i-Tree is a data-driven tool based on the forestry inventory, which estimates tree benefits and management costs. The tool reports annual total and per tree values[32] for energy conservation, storm water drainage, air quality improvements (SO_2, NO_2, PM_{10} and volatile organic compounds VOCs), CO_2 reduction and aesthetic value realised through property price differences. Reviews of i-Tree can be found in Sarajevs (2011) and Eftec (2013). The first British council to trial i-Tree was Torbay, Devon, and the tool has subsequently been applied in Edinburgh, Wrexham and Glasgow. A summary of the values of the benefits of urban trees estimated using i-Tree for Wrexham and Glasgow (Rumble *et al.*, 2014, 2015) is provided in Table 10.2. In 2015 the London Tree Officers Association led a survey of London trees which formed a data layer for a London-based i-Tree application reported in December 2015 (Rogers, Jaluzot and Neilan 2012).

[32] Values in i-Tree are estimated in US dollars (US$). Local calibration adjusts these values based on population density, income and exchange rates. Value estimates are obtained using hedonic analysis and sewage treatment costs.

Table 10.1 A summary of urban tree based tools.

Tool	Scale	Valuation methods	Ecosystem services	Latest updates	Uses
i-Tree Eco	Individual trees and urban forests	Hedonic analysis Sewage treatment costs	Carbon dioxide reduction Storm water capture Air pollution Energy savings	UK parameters Treeconomics – London tree survey Applications in Torbay, Devon, Wrexham and Glasgow	Assessment of the benefits of any size of urban forest for planning, management and maintenance decisions
CAVAT	Individual urban trees	Nursery gate price Costs of planting and maintenance	None	Adjusted for inflation Unit value factor of GBP 15.88 per cm^2	Securing compensation for damage to council trees
Helliwell	Individual urban trees and woodland	Point-based scoring based on factors including tree size, life expectancy and location The economic basis of the unit value is not explained	Visual amenity (aesthetics)	Current Helliwell point values (from 1 January 2015): Individual trees: GBP 30.84 Woodlands: GBP 123.36	Describing costs and benefits for insurance claims and public inquiries

Table 10.2 Values from existing i-Tree applications – Wrexham (Rumble *et al.*, 2014), Glasgow (Rumble et al., 2015) and Greater London (Rogers, Jaluzot and Neilan 2012).

Benefit	Values		
	Wrexham	Glasgow	Greater London
Carbon storage	GBP 14 000 000 Value of discounted stored tCO_2e GBP (2013)	GBP 40 000 000 Value of discounted stored tCO_2e GBP (2013)	GBP 142 000 000 Value of discounted stored tCO_2e GBP (2015)
Carbon sequestration	GBP 24 000 per annum	GBP 1400 000 per annum	GBP 4630 000 per annum
Water interception	GBP 460 000 per annum	GBP 1100 000 per annum	GBP 1191 821 per annum
Air pollution removal	GBP 700 000 per annum	GBP 1400 000	GBP 125 000 000 per annum
Energy savings	GBP 637 500 per annum	GBP 2750 000 per annum	GBP 315 477 per annum
Total value	**GBP 2037 000 per annum**	**GBP 6650 000 per annum**	**GBP 130 821 000 per annum**
Population (Office for National Statistics, 2012)	134 844	593 245	8200 000
Value per capita	GBP 15.11	GBP 11.21	GBP 15.95

Originally developed for the USA, i-Tree Eco (one of the i-Tree suite of applications) can be applied to the UK through changing the carbon and energy calculations using the conversions produced by Rogers, Jaluzot and Neilan (2012). With these conversions, and guidance from ecologists and economists, the tool can be applied to the UK to estimate the economic value of climate regulation, water regulation and air quality regulation.

Capital Asset Valuation for Amenity Trees (CAVAT, 2010)

CAVAT is an asset management tool, which calculates depreciated replacement costs per tree adjusted for tree health, location and accessibility, amenity and social value based on trunk area. These adjusted costs are converted into an index, which rises and falls to reflect changes in the quality and characteristics of the tree stock over time.

The methodology used in CAVAT is inconsistent with the principles of economic valuation (see Eftec (2013) for a detailed discussion on this). Although CAVAT accounts for social and amenity value it does this by scaling a unit value factor (per cm^2) to reflect the relative proportion of total social and amenity value provided by a particular tree. This is not equivalent to estimating the economic value of these benefits since the unit value factor is based solely on the cost of a newly planted tree in a given area and the scaling is based on expert judgement (Neilan, 2010).

Helliwell

The Helliwell system uses a similar methodological approach to CAVAT in that points are allocated based on the characteristics of the tree or woodland and combined to give a comparative score; this score is then multiplied by a fixed unit value. Unlike in CAVAT, the unit value in the Helliwell system does not vary across different types of trees or woodlands. The points system is explicitly based on expert judgement to incorporate the life expectancy of the tree and its aesthetic (visual amenity) value taking account of the importance of position in the landscape and relation to setting (Price, Thornton and Nelson, 2007).

The Helliwell tool has been used in court cases and for insurance claims and public inquiries (Eftec, 2013); however, as with CAVAT, the tool is not recommended for economic valuation because the methodology does not attempt to estimate the value of the environmental and social benefits provided by woodlands.

Amenity values

Urban trees provide both positive and negative amenity values. For example, trees and woodlands located near to a property can provide aesthetic value; however, they may also block out light or cause structural damage to properties. Mourato *et al*. (2010) undertake a hedonic property pricing analysis to predict house price differentials that can be attributed to variations in the level of environmental amenities across England. This is achieved by holding constant the difference in house types and non-environmental characteristics across areas and only looking at the impact on house prices arising from variations in environmental quality. While this approach produces implicit prices for access to environmental amenities, such as trees and woodlands, it is difficult to disentangle different components of value and understand what portion of that value is for access to woodlands for recreation, amenity value, air quality improvements, noise reduction or perceived health benefits and so on. This is problematic in terms of aggregating values as it produces a risk of either double counting or accidentally omitting values for particular benefits.

Uses

The UK's Town and Country Planning Act (1990) places a duty on local authorities to protect the public amenity value of trees. The existing evidence base and tools have been used by local authorities to support this effort in a number of ways. These include:

- local planning, management and maintenance of urban trees (i-Tree)
- legal cases to claim compensation for damage to council trees (CAVAT)
- the calculation of damages for insurance claims (Helliwell)
- public inquiries (Helliwell)

There is also scope for using these tools to inform natural capital accounts and corporate natural capital accounts (see Section 13).

Research gaps

Water resources

- i-Tree Eco provides a useful resource for estimating the impact of urban trees and woodlands on storm water drainage. However, since the hydrological models were developed in the USA and are closed within i-Tree Eco it is difficult to assess the transferability of the model to the UK setting.

- There is limited existing information on the relationships between urban trees and water quality, including their role in reducing sewage treatment costs and improving urban recreation. Estimates of the impact of urban trees on water resources at recreational sites and the resultant impact on the value of recreational visits could be constructed by using general biophysical studies on the impact of trees on water quality and valuing the impact of the change in water quality on recreation, taking into account the location of the recreation site (allowing for distance decay and proximity to population).
  Adopting this approach requires an implicit assumption that the biophysical process is the same in urban and rural areas, or that any important scaling factors (such as tree density, nutrient concentration, flow rates and distance from sewage works) were represented in the sampled data and have been controlled for.

Air quality

- The literature relating urban trees to air quality suffers from the same limitations as for water resources. Although there are simulation models relating individual tree species (controlling for maturity) to air filtration (Donovan *et al*., 2005), these models are based on underlying biophysical studies which sample larger woodlands (greater than 2 ha). Moreover, there is uncertainty over the rates of absorption and deposition and there is very little discussion of whether these rates are likely to be the same in urban and rural areas (Powe and Willis, 2002, 2004).

Health values

- The key challenge in valuing the physical and mental health benefits provided by urban trees and woodlands lies in developing a clear understanding of the biophysical processes at work.
- There is some existing evidence on the physical health benefits provided by trees and woodlands; there are studies linking greenspace to exercise and physical health, and evidence of links between trees and water quality, air quality and climate (see Sections 2-6 for further details). The challenge in this area is to understand whether these relationships hold, or are augmented, for urban trees as a subset of greenspace.
- Evidence on the mental health benefits provided by trees and woodlands is undergoing substantial but slow development. A major challenge in this area is presented by the need for a common generic and comparable metric for measuring mental health. In addition, the existing evidence is often highly localised and difficult to interpret without a suitable control study. A major gap in this area is the development of rigorous, generalisable and comparable studies of the biophysical processes.
- The Health Economic Assessment Tool (HEAT) is available from the World Health Organization Regional Office for Europe. HEAT provides values for the benefits derived from habitual walking and cycling as recreational activities using the UK Value of Statistical Life discounted with a default discount rate of 5%.[33] However, the tool does not disaggregate the benefits by particular types of green infrastructure. As a result, reporting the total value will overstate the benefits from urban trees and woodlands, or alternatively scaling for the proportion of total green infrastructure that is trees and woodland makes the assumption that green infrastructure is perfectly substitutable.

Climate

There is significant evidence for the climate-related benefits of urban trees and woodlands.

- There is a broad literature on the biophysical processes and economic values related to urban cooling services by shade trees in the USA (Akbari, 2002; Nowak *et al*., 2010, 2012). Using data on indoor and outdoor temperature and humidity, wind speed and direction and air-conditioning cooling energy use, Akbari *et al*. (1997) show that shade trees near houses can yield seasonal cooling energy savings of approximately 30%. Given the relative temperatures and prevalence of air conditioning in North America relative to the UK, it is possible that energy savings may be lower in the UK. However, if future studies also incorporated potential health impacts (of reducing urban heat island during summer heatwaves, reduced dehydration, heat stroke), the overall value of urban cooling services from trees could remain substantial.

Recreation

- Urban trees and woodlands provide opportunities for recreational experiences in an urban landscape, which is a mosaic of different land uses and in close proximity to densely populated residential and commercial areas. The evidence for recreational values from urban trees and woodlands is relatively robust (Brander and Koetse, 2011; Perino *et al*., 2014); however, none of the urban valuation tools reviewed here currently incorporate recreation into their valuation calculations.
- Bateman, Abson *et al*. (2011) and Bateman, Day *et al*. (2014) show how location of recreational sites matters. A

[33] Users are able to override this default value, and we recommend using the official UK Treasury procedure for discounting.

recreational site can generate a significant range in values depending on where it is located. The critical determinant of this range is, perhaps not surprisingly, proximity to significant conurbations, and thus the study of recreation values in urban areas is particularly salient.
- Recreation businesses (e.g. b&b, tourist destinations).

Biodiversity

- Johnston, Nail and James (2011) discuss the debate among urban forest professionals regarding the role of exotic versus native tree species and their contribution to urban biodiversity in Britain. They assess the current evidence and conclude that an automatic preference for native species cannot be justified, and that biodiversity and the wide range of services provided will be restricted by just selecting from the few native species that thrive in urban environments.
- Croci *et al*. (2008) suggest that effective management of urban woodlands could be a good option for promoting biodiversity in towns, and Davies *et al*. (2009) and Cameron *et al*. (2012) suggest that domestic gardens also provide an important contribution to UK biodiversity habitat and hence conservation. What is important in management and new planting decisions is a scientific understanding of the roles of particular species and the complex interactions in urban ecosystems.

11. Issues arising from gains and losses

Incomplete gains and losses

When considering the value of the economic and social benefits of trees and woodlands it is easy to conceptualise a whole tree or an entire woodland; however, it is also important to understand that in many cases what we want to value are things such as a change in the quality of the trees due to pests, disease or management, or a change in the composition of a woodland due to the loss of a species. We refer to these sorts of changes as incomplete gains or losses.

There is some evidence exploring the impact of tree quality on the health benefits provided by trees and woodlands. For example, using the spread of ash borer in the Midwest as a natural experiment, Donovan *et al*. (2013, 2015) provide an investigation of the relationship between the spread of ash borer and the incidence of cardiovascular disease at county level and among women, respectively. Donovan *et al*. (2013) found that infested counties had increased rates of cardiovascular and lower-respiratory mortality, and that this relationship was increasing as the infestation progressed. Likewise, Donovan *et al*. (2015) conclude that, after controlling for other factors, women living in counties infested with emerald ash borer had a 25% higher risk of cardiovascular disease. Valuing such changes in tree quality requires us to value incomplete losses such as a change in the health of individual trees or loss of particular species within a woodland.

Incomplete gains and losses are dealt with in a relatively robust manner in the context of urban tree based tools. For example, the values in i-Tree Eco take into account the species, size and ecological condition of each tree surveyed, CAVAT includes a quality index to reflect the health of the tree and Helliwell incorporates expert judgement on the life expectancy of the tree and its aesthetic value. However, as discussed in Section 10 only i-Tree Eco provides values which are consistent with the principles of economic valuation. i-Tree Eco provides a means of calculating estimated values for incomplete gains and losses relating to carbon emissions, storm water capture, air pollution and energy savings.

Research gaps

The valuation of recreational benefits (costs) from incomplete gains (losses) presents a notable gap in the existing literature. This presents a challenge if we believe that the value of woodland recreation sites is related to the quality of trees at the site (e.g. species type, canopy size, tree density and tree health). There is little evidence to support or negate this; however, it seems possible that tree diseases with physical symptoms will affect the value of recreational visits. With the number of tree disease incidents rising (Figure 9.1), this is an area of increasing interest and concern.

Asymmetry in gains and losses

A further challenge that arises in valuing the social and environmental benefits provided by trees and woodlands is that the value of a gain is not the same as the value of a loss, even when these are of the same magnitude (e.g. the gain or loss of a single tree). For example, an additional tree in a woodland of 10 trees may not add much value in terms of recreation, visual amenity and habitat for wildlife. However, losing one of these 10 trees may be very valuable: for instance if this loss reduces the size of the woodland such that it can no longer support the wildlife in the habitat, or if it leads to a significant reduction in angle subtended (proportion of the field of vision containing trees). The asymmetry between the value of gains and losses can affect amenity values related directly to trees and woodlands (such as changes in aesthetic value or the quality of woodland recreation sites) as well as the value of final environmental goods and services provided by trees and woodlands (such as changes in water quality).

Differences between valuing gains and valuing losses

One of the central asymmetries between gains and losses in woodlands arises from the biophysical functioning (and resulting flow of environmental goods and services) that is gained or lost.

- The loss of woodland often means a reduction in the quantity or quality of established woodland. This could be due to a change in land use (e.g. thinning, felling) or due to disease (e.g. the environmental function of the tree is lost). The value of the loss will also depend on what replaces the existing woodland (e.g. this could be a diseased woodland, cleared woodland or alternative land uses such as grassland or crops).
- Gains in woodland are achieved by converting existing land use (e.g. agriculture) to woodland or by improving tree health. Newly planted trees take time to grow and become established. During this time they provide a different (and potentially smaller) flow of environmental goods and services to an established tree. For example, saplings provide very different aesthetics, habitat and

environment for recreation in comparison to established or ancient trees. As a result, gains and losses in plant health are likely to be more comparable than gains and losses in entire trees or woodlands.

Non-linearities also cause problems in applying values related to gains to value losses and vice versa. If the total quantity of the stock of trees or woodland in a given area falls this can lead to very different outcomes.

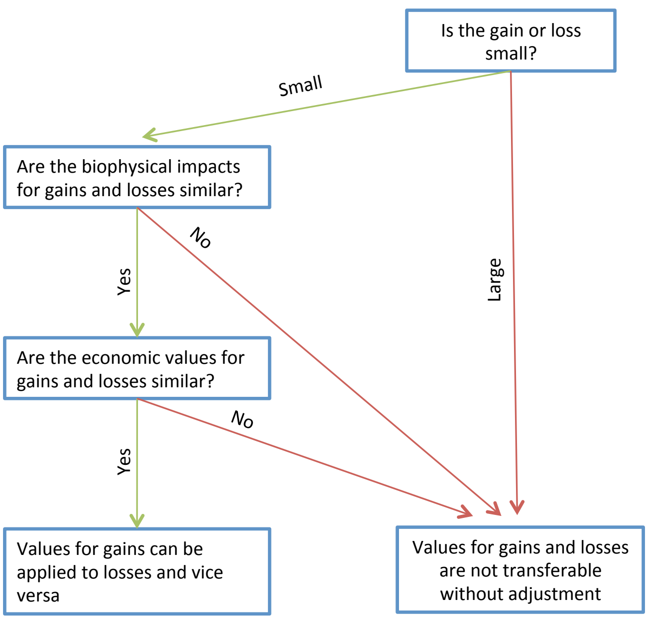
- Non-linear biophysical processes: This could be important for soil regulation, flood protection and habitat provision. A loss in the number of trees close to a threshold for any of these services would cause a much larger loss in value than the comparable gain from an equivalent gain in the number of trees (e.g. a minimum viable habitat size may be required in order to support a population of woodland birds).
- Non-linear economic value: A reduction in the total size of a woodland could cause it to be unsuitable for certain types of recreation, leading to a much larger willingness to accept value for a loss than the willingness to pay value for an equivalent gain. This is likely to be associated with relative scarcity – a gain or loss in a situation of relative abundance (or scarcity) is likely to have similar approximately linear impacts. For example, the visual amenity value of one additional oak tree in my view when there is currently only one is likely to be highly valuable, and losing one when I only have two can be expected to be comparable. Conversely, an additional oak tree in my view when there are 500 as part of a woodland is likely to be of small marginal value, as is the loss of one.
- Endowment effects: Psychological rather than rational elements of preferences can also create an asymmetry between the values of gains versus losses. For example, in stated preference studies the value of a good has been shown to differ depending on whether the good already belongs to the person. This is a complex concept, which was confirmed through economic experiments in which half of a group of people were given a mug and the others were not. People with a mug were asked how much they would sell it for and people without a mug were asked how much they would pay to buy one. People who were given a mug asked to be paid at least two and a half times more than people without a mug were willing to offer. In terms of gains and losses, buying a mug is a gain and selling a mug is a loss; this suggests that losses are valued more highly than gains. This phenomenon was termed an endowment effect in the seminal papers of Kahneman and Tversky (1984) and Kahneman, Knetsch and Thaler (1991). In the context of trees and woodlands, the endowment effect is more complex because trees and woodlands (including to some extent private woodlands) are public goods, which provide the general public with a sense of communal ownership. This sense of ownership could lead to an endowment effect over existing trees and woodlands. As a result, the value of gaining one new tree is likely to be lower than the value of losing an existing tree.

Using gains to value losses and losses to value gains

Collecting data for primary valuation studies on both gains and losses for each species of tree at different spatial and temporal points would be time consuming and expensive. As a result, it may be more pragmatic to try to use the same values, or use a benefit transfer function to apply values relating to gains in trees and woodlands to losses and vice versa. Determining whether this is appropriate requires an understanding of the biophysical and economic differences between gains and losses.

If both the biophysical processes and economic value functions are linear, or the change in the quantity or quality of woodland is marginal, and there are no endowment effects then there is no problem in applying values estimated for gains in trees and woodlands to losses and vice versa. In situations where gains and losses are likely to result in very different impacts, in terms of biophysical processes, economic value functions (i.e. due to non-linearities as discussed above) or substantial endowment effects this approach is likely to lead to an underestimate or overestimate of the value of the change. Figure 11.1 provides an illustrative decision tree for determining whether gains and losses are transferable.

Figure 11.1 Valuing gains using losses and vice versa.



12. Integrated assessment and decision-making tools

Amid growing recognition of the natural environment's role in generating human well-being, a series of ecosystem service decision support tools have been developed to guide decision-making. These vary in sophistication from simple spreadsheet tools to complex software packages integrating biophysical, GIS and economic models (Bagstad *et al*., 2013) and draw upon many fields, including ecology, hydrology, geography, systems theory, economics and the social sciences. They also differ in their ability to value changes in ecosystem services and handle various spatial and temporal scales, data and computational constraints, and conflicts between users, science and data (van Delden *et al*., 2011).

A new class of integrated ecosystem service mapping tool including InVEST, LUCI, MIMES and The Integrated Model (TIM, developed by CSERGE and outlined in detail below) is beginning to emerge. These tools incorporate state-of-the-science biophysical models to reflect interactions between multiple ecosystem services at various spatial and temporal scales. Their process-based biophysical underpinnings enable these tools to use information from areas with high data availability to model environmental processes and relationships in areas where data are relatively scarce (Bateman *et al*., 2011). This greatly enhances coverage, and thus the likelihood that a given tool can be applied to specific policy questions. These tools are described below and summarised in Table 12.1.

Two of the best known ecosystem service tools are InVEST (Sharp *et al*., 2014) and ARIES (Bagstad *et al*., 2011). InVEST currently considers water quality, soil conservation, carbon sequestration, biodiversity conservation, aesthetic quality, coastal and marine environment vulnerability, hydropower production, pollination services and values of selected market commodities. Its models are biophysical, and include explicit economic valuation of all services. The most recent release of ARIES includes carbon sequestration, flood regulation, water supply, sediment regulation, fisheries, recreation, aesthetic viewsheds and open-space proximity value. It is designed to be extremely flexible and can include biophysical models where desired, but generally uses empirical statistical approaches to extract relationships between inputs and outputs. However, ARIES does not provide economic values.

Other tools gaining interest are MIMES, LUCI and Co$ting Nature. For a review, see Bagstad *et al*. (2013). MIMES is a systems model which represents the dynamics and feedback loops between physical, social and economic processes. It seeks to be a truly integrated model, and represents an ambitious effort to take integrated modelling forward to match or extend the state of the art of meteorological and climate modelling to economic models. LUCI is highly spatially explicit (with resolution of 5-m grid squares within the UK and at worst 50 m by 50 m globally) and may therefore be applied at any spatial scale, say for considering the cumulative impacts of small interventions such as riparian planting at national scale. It currently considers agricultural productivity, flood regulation, carbon sequestration, sediment regulation, habitat connectivity and water quality. It has a simple approach to considering trade-offs between services, classifying individual service provision at its native spatial resolution into 'existing good', 'potential to improve', or negligible existing or potential provision'. It then layers those categorised services to identify parts of the landscape where trade-offs versus win-win situations exist, and where management interventions could enhance or protect multiple services. Finally, Co$ting Nature uses global datasets to estimate and value water yield, carbon storage, nature-based tourism and natural hazard mitigation services, aggregating these into a 'service index' accounting for not only provision but also beneficiary location. Although it is less flexible and modular than the other frameworks, it is significantly easier to apply (and access). Table 12.1 offers a brief comparison of TIM against five common ecosystem service decision support tools. A more detailed comparison may be found in Bagstad *et al*. (2013) and Bateman, Day *et al*. (2014).

TIM is the first application of an integrated modular ecosystem service framework covering the whole of the UK and using detailed UK-specific data (we discount 'global' applications, using coarser global data, such as MIMES (Boumans *et al*., 2015) and Co$ting Nature). Compared to the established suite of ecosystem service models, TIM's novelty lies in the introduction of formal optimisation alongside ecosystem service valuation. Crucially, because services are valued in common economic units, trade-offs and comparisons can be drawn and their impacts can be readily interpreted by a diverse audience of varying specialist backgrounds. This is particularly useful in land-use policy as decision-makers are expected to maximise net benefits derived from the scarce resources at their disposal, accounting for a broad range of biophysical and economic impacts and responses. Although InVEST also applies economic valuation, it stops short of formal optimisation and lacks the rich, custom dataset at the 2 km grid square resolution used by TIM in the UK.

TIM has been used to model and value land-use policy impacts throughout the UK, and in particular has been applied to a proposed afforestation policy of planting 5000 ha of new woodland per annum for each year between 2014 and 2063 in each of England, Scotland and Wales, yielding an increase in overall forest extent of 750 000 ha. In undertaking this analysis, TIM develops a series of individual, yet interlinking modules that analyse land use at the 2 km grid square resolution. Together, the biophysical and economic modelling is able to report values for changes in market production, market production plus greenhouse gas implications, and the social value (market production, greenhouse gases and outdoor recreation).

TIM's farm module develops an econometric model linking climate change to farm level decisions regarding crop and livestock production. This in turn drives changes in agricultural runoff (described by a water quality module); agricultural greenhouse gases (CO_2, N_2O, CH_4; described in a farm greenhouse gas module); and farm bird species (described in the biodiversity module). The impact of climate change on timber production is considered within the timber module, which also incorporates forestry decisions (which species to grow, rotation periods and management practices), and the resulting greenhouse gas implications (sequestration in livewood, emissions from felling waste, emissions and sequestrations from various types of soils) are described in the forestry greenhouse gas module. An innovative recreation module developed a new random utility model (see Section 5) to analyse and value the impact of land-use change on outdoor recreation and associated travel costs. Crucially, TIM makes it possible to explore how the availability of substitute recreation sites impacts values, and how this changes over time as new substitutes become available. Finally, a biodiversity module links to the farm and timber models to identify the impact of land-use change on wild bird species. Owing to the difficulty of directly valuing biodiversity, TIM instead explores the welfare impact of imposing various 'biodiversity constraints' such as requiring no net loss in biodiversity.

While its initial case study considers the implications of an afforestation policy, TIM was developed with a high degree of flexibility and is readily applicable to a range of other policy-relevant questions (e.g. impact of new agricultural subsidies and the costs of meeting various water quality or biodiversity regulations). Moreover, the modular approach makes it possible for each component to be developed and improved independently and for new modules to be included in future analyses. Due to the modularity of the integrated approach, any component system can be removed, improved, added or replaced in a way that maintains consistency with any other system. This means that as more sophistication is added there is potential to optimise across a wider suite of social values and drivers of change. As with the nature of research, as more knowledge is amassed, modules are refined.

Further research will consider a more robust optimisation methodology under conditions of uncertainty. The methodology will attempt to optimise when there are uncertainty bounds on the nominal annuity values; as an analogy consider stock portfolio selection where the aim is to seek an optimal value while limiting the downside risk as much as possible. Uncertainty in carbon price is an initial consideration. An important extension of this research is to incorporate non-monetary constraints on policy and planting options. These could include, for instance, a requirement that any planting which reduces bird species diversity in an area be rejected (e.g. Bateman, Harwood *et al*., 2013). In addition, constraints on water quality could also be considered.

Of course, no appraisal of a complex system such as land use will ever be absolutely complete. Similarly, a modelling exercise will always be, to some extent, an abstraction from reality. The criterion here is not to attain a perfect replication of land use and its determinants, but rather to deliver a robust analysis that reliably captures the major drivers of change and their associated trends. This research is undergoing continual refinement: from modifications to modules representing impacted systems to how this new approach of policy targeting (considering the natural environment) is presented to decision-makers.

Perhaps the most fundamental research gap concerns the need to integrate natural science, economic and social science understanding of the multiple net benefits provided by changes in the extent and management of trees and woodlands in the UK. The current incomplete and fragmented science and valuation literature suggests that the diversity and integrated nature of woodland benefits leads to their systematic under-reporting. This in turn is likely to result in under-investment and substantial foregone values. A comprehensive extension to our understanding of these issues is therefore a significant priority for decision support.

Table 12.1 Overview and comparison of integrated ecosystem service assessment tools.

	ARIES	Co$ting Nature	InVEST	LUCI	MIMES	TIM
Model approach	Bayesian belief network and agent-based modelling; flexible framework	Web-enabled model with globally available data using simple empirical models	Detailed biophysical models and economic valuation of all services	Simplified biophysical models with fine spatial detail; fast running for scenario exploration	Detailed physics and integration of environmental, economic and social drivers	Biophysical modules with robust economic valuation and formal optimisation
Spatial scale of analysis [resolution of individual elements in brackets if applicable]	Flexible, but generally regional scale	Flexible, has global coverage [1 km^2 or 1 ha]	Regional – component models not suited for local scale application	Sub-field to national [typically 5 × 5 m 50 × 50 m]	In theory flexible, to date regional to global	Medium catchment to national [2 km grid square]
Temporal scale of analysis	Flexible	Steady state	Annual, sub-annual in development	Steady state and annual, sub-annual in development	In theory flexible; data requirements currently limiting	Annual but could be sub-annual
Data gathering effort required by user	Heavy for new applications (existing applications will be made available via web portal)	Negligible; data pre-loaded and available via web portal	Heavy	Moderate; 'first tier' suite of models work with widely available national data	Very heavy	Negligible; data are pre-loaded and available within the TIM software
Flexibility/ modularity	Very high	Low	High	High	N/A – fully integrated systems model, component processes could be modularised but not services	High, with built-in constrained optimisation procedure
Economic valuation provided?	No	No	Yes	No	In theory; due to type of model perhaps not fully yet	Yes
Types of trade-offs considered	Biophysical and via analysis of service flow from provision to beneficiaries	Services categorised and flow to beneficiaries considered	Biophysical and monetary units traded against each other	Biophysical; 'win-win' vs. trade off analysis of categorised services	Economic valuation of services and analysis of their interactions	Trade-offs analysed by explicit economic valuation of all services
Optimisation?	Through scenario optimisation; although Bayesian framework potentially enables robust optimisation and uncertainty analysis	Through scenario optimisation only	Through scenario exploration only	Through scenario exploration, some guidance on optimisation given via maps showing regions where preservation or change desirable	Through scenario exploration only	Yes, constrained optimisation procedure is part of framework. This allows policy-makers to explore the best way to achieve their objectives, with the ability to adjust the definition of what constitutes a 'best' outcome
Unique features	Sophisticated modelling of flows to beneficiaries, source and sink, flexibility, Bayesian and agent-based modelling	Globally available, simple to use, data pre-loaded for user	Most established/ advanced suite of biophysical models, explicit economic valuation	Designed to work with nationally available data, spatial scale scans sub-field to national, fast running to enable real-time stakeholder exploration	Full systems approach, truly integrated model	Constrained optimisation procedure; explicit economic valuation; increased integration via coupling linkages between services Contains an economic behaviour model responding to changes in market, policy and environment

13. Natural capital accounting[34]

'National accounts are like sausages: everybody loves them, but nobody wants to know what's in them.'[35]

Natural capital is the stock of physical assets that generate flows of environmental goods and services that benefit people. Though the increasing popularity of the term 'natural capital' is encouraging, a proliferation of inconsistent definitions could render it a mere buzzword, serving as a 'catch all' phrase for all things 'green'. This would be an unfortunate loss. The chief motivation for adopting the term natural **capital** (rather than 'the environment') is to distinguish it as capital, and apply our understanding of how to value capital stocks, manage net investments and utilise flows of capital services in production.

Like all capital, natural capital consists of stocks that persist through time. It refers to environmental assets that contribute to the production of flows of valuable goods and services. For example, a country's stock of woodland is a natural capital asset that generates flows of environmental goods (e.g. timber) and services (e.g. clean water and air, equable climate, recreation sites). Recalling the ecosystem services paradigm set out in Section 1 of this report, we know that in most instances natural capital is combined with other forms of capital to generate benefits for people.

Modern economies rely upon a combination of multiple forms of capital to produce consumption goods. These capitals include:[36]

1. Produced capital – physical infrastructure, machinery, housing stock and so on.
2. Human capital – people, the labour force, skills and knowledge.
3. Natural capital – ecosystems, species, fresh water, land, subsoil assets and so on.
4. Social capital – trust, adherence to a 'social contract'.
5. Institutional capital – governance, rule of law, financial regulations.
6. Financial capital – savings and investment.

[34] This section draws from Agarwala (in preparation, a) and Agarwala *et al*. (in preparation, b).
[35] An adaptation of 'laws are like sausages, it's best not to know what's in them' often attributed to Otto von Bismarck.
[36] There is no firmly established categorisation of types of capital. Some authors will refer to these six, but it is sometimes helpful to disaggregate further in order to focus on specific elements of wealth. Others will aggregate, perhaps referring to human, natural, produced and 'intangible capital', which acts as a catch-all term for elements that are particularly difficult to define and measure (e.g. social and institutional capital). For simplicity, theoretical investigations in particular often consider just two forms of capital: one being the asset of interest (e.g. natural capital) and a second, 'composite capital', which represents all other forms of productive asset in a single entity.

In enjoying the recreational opportunities provided by UK woodlands, a family might save for a holiday (employing financial and institutional capital), drive across the country (making use of produced capital) and spend a week at a campground enjoying woodland walks (making use of natural and produced capital).

Conceptually, natural capital is similar (but not identical) to other types of capital produced by humans. For instance, a vehicle manufacturing plant is a produced capital asset that produces flows of goods (cars) over time. Overuse wears down heavy machinery (depreciation). If the rate of depreciation is greater than the rate of reinvestment (capital maintenance expenditure), future output falls. Both the manufacturing plant (capital asset) and the flow of goods (cars produced) have economic prices that, even if they cannot always be directly observed, can be estimated and reported according to formal accounting rules. In economic terms, the value of a capital asset is simply the net present value of the complete flow of future goods and services it generates.

Similarly, stocks of natural capital assets generate flows of environmental goods and services over time. Forests and fisheries are like 'natural factories' (see Section 1) producing flows of timber and fish. These capital assets are depleted and degraded by excessive pollution and overharvesting (depreciation), and future output will fall if this depreciation exceeds the combined rate of natural regeneration and human investment in natural capital maintenance (e.g. planting new forests, environmental restoration, conservation investments). Here lies the first major difference between natural and produced capital: unlike vehicle manufacturing plants, many natural capital assets are capable of repair and regeneration[37] without the intervention of humans and alternative forms of capital. The capacity for regeneration is a central feature of natural capital and can be enhanced or eroded by human activity.

Insofar as they generate flows of final environmental goods and services (FEGS), these 'natural factories' (natural capital assets) also have economic value, defined in terms of the net present value of the complete flow of future goods and services they generate. But here we find two further points of departure between natural assets and their produced capital counterparts. First, it is often far more difficult to identify, measure and value the future flows (of FEGS)

[37] This natural regenerative capacity can be enhanced by human activity, as it is when higher concentrations of atmospheric CO_2 boost plant and tree growth, or degraded by it, as it is when habitat destruction pushes wildlife towards extinction.

generated by natural capital than it is for produced capital. Second, while market prices for produced capital and the goods and services it generates can be recorded from readily observable market exchanges, the production of environmental goods and services by many natural capital stocks takes place outside the formal economy, and therefore no readily observable market exchanges take place. This poses a series of unique challenges for those wishing to develop a monetary estimate of the role that natural capital plays in the economy. These challenges form the basis of current debates around natural capital accounting (and in particular how natural capital relates to ecosystem service valuation and other national accounting standards) and are the core focus of this section.

Natural capital accounting activities

Growing recognition of its importance to modern economies has attracted considerable attention to the development of methods for measuring, monitoring and valuing natural capital. As a result, a broad range of activities now claim to fall under an umbrella heading of 'natural capital accounting'. Briefly, these efforts can be categorised as:

1. Wealth accounting: Comprehensive, or inclusive wealth refers to the economic value of an economy's total capital stock, including all of the types of capital described above. Comprehensive wealth encompasses the economy's total productive capacity, and therefore determines the prospects for future consumption. Wealth accounting has strong foundations in economic theory (Solow, 1974; Hartwick, 1977; Arrow *et al*., 2012) and underpins economic definitions and indicators of sustainability (Atkinson *et al*., 2014). Here, the value of capital assets is defined by the contribution they make to future well-being, which is often simplified in empirical applications to mean 'the contribution they make to future consumption'. In practice, actually measuring comprehensive wealth (and changes in it) is an active but challenging area of research (Pearce and Atkinson, 1993; World Bank, 2006, 2011; UNEP, 2012; UNU-IHDP and UNEP, 2014). This is because the valuation challenge is not limited to natural capital, but also extends to many other types of productive assets, including institutional, social and human capital.
2. National accounting: This is adjusting or augmenting the national accounts so that they 'better reflect' the relationship between environmental stocks and flows and national economies. While this is the area of 'natural capital accounting' that has attracted the greatest policy attention (indeed this is the aim of the Office for National Statistics – *Natural capital accounting 2020 roadmap*), it is also the area where loose definitions and conceptual inconsistencies may generate the greatest confusion. Some of this can be reduced by making a clear distinction between valuing natural capital stocks and valuing the flows of FEGS those stocks produce. Strictly speaking, natural capital accounts should contain values for natural capital stocks, which is different from values of flows of FEGS. Of course, the value of a natural capital asset and the value of the FEGS that it produces are intimately related: formally, the value of a natural capital asset is simply the summed value of all the future flows of FEGS that it generates, discounted to the present time[38] (i.e. the net present value). How values for natural capital stocks relate to values of flows of FEGS, and how both could be related to the national accounts is discussed in further detail below. It is important to note the distinction between natural capital accounting efforts for wealth versus national accounting: wealth accounts require natural capital values that reflect the contribution of natural assets to future well-being, whereas national accounts require values that reflect contributions to current macroeconomic indicators such as gross domestic product (GDP). This is an important distinction as a contribution to well-being and a contribution to GDP are not necessarily equivalent. In practice, however, using data from national statistical offices may be a justifiable pragmatic compromise for wealth accountants.
3. Corporate natural capital accounting: Without discounting the importance of government policy, it must be recognised that, in many instances, natural capital assets are owned and managed by the private sector. For example, 75% of the surface area of Great Britain is dedicated to agriculture, and 100% of that is private sector. Similarly, extractive industries, water companies and energy utilities are all private sector agents with substantial impacts on natural capital. Businesses are also increasingly aware of their own impacts and dependencies upon natural capital and some firms are developing 'natural capital accounting' mechanisms of their own in order to identify potential risks and opportunities related to natural capital. In 2015, the UK Natural Capital Committee produced formal guidance documents for the development of corporate natural capital accounts, the Natural Capital Coalition is developing further guidance, and Office for National

[38] Although this definition is theoretically sound, it does rely on a number of powerful assumptions. If the conditions set out by these assumptions are not met, the accuracy with which the value of natural capital can be derived from the net present value of FEGS is greatly diminished. The assumptions include:
1. Perfect information. This requires that the full stock size (even of as yet undiscovered wild species and subsoil assets) is known, as is the full suite of future technologies and policies that might affect how FEGS are used in production.
2. Perfect competition.
3. Complete markets.

Statistics activity around national natural capital accounting may also serve as a signal to the private sector.

4. **Biophysical natural capital accounts**: Before any of the exercises described above can be pursued, it is a necessary prerequisite to established detailed biophysical inventories of natural capital stocks. Such accounts are fundamental to identifying and understanding trends in resource use, regeneration and depletion, indicating possible tipping points, and establishing the capacity of the stock to support ecosystem function. To provide the most useful information (including to users beyond economists and national accountants) biophysical natural capital accounts should also be spatially referenced. There is strong potential for such accounts to provide further functions in serving as a consistent repository for regular data collection, biophysical inventories and ecosystem monitoring.

There are multiple potential uses for natural capital accounts, and the extent to which accounts are 'fit for purpose' will depend on how they are designed. For example, multinational corporations may wish to develop natural capital accounts that trace natural capital impacts and dependencies in multiple countries along a global supply chain, whereas national governments may wish to focus specifically on the natural capital within their borders. At the national level, accounts could help to identify those natural capital assets that are at greatest risk and which may therefore be high priority areas for conservation (either because they generate substantial value or because ecosystem services are under pressure), setting environmental targets (e.g. no net loss of biodiversity, or maintaining or expanding the national stock of forests) and measuring progress towards achieving them, serving as an evidence base for developing forestry and land-use policy, and formally recognising the contribution of natural assets to the economy. Finally, because accounts tell a story over time, accounts developed now will become increasingly useful as the trends they identify can be increasingly related to other variables of interest. The uses of GDP accounts, for instance, have grown substantially since they were first developed in the 1930s.

National accounting

On first pass, the notion of 'incorporating the value of natural capital into the national accounts' seems an admirable objective. However, several conceptual and practical realities must be considered. Earlier sections of this report and the discussions immediately above set out a consistent conceptual framework for considering natural capital as a set of productive assets generating flows of environmental goods and services, of which some serve as inputs into production in the human economy. Many of these FEGS can be valued, as shown elsewhere in this Report. The Woodland Valuation Tool, provides a broad review of recent valuation exercises across the UK and internationally. Before these concepts and values can be linked to the national accounts, we must first consider what national accounts are, and what they are not.

National accounting is a method of collecting, organising and reporting desirable information on economic activity that is ultimately relevant for measuring trends and making decisions. Here, desirable is key. National accounts and their constituent parts are not determined by economic theory, nor are they necessary fundamental components of a working economy (the UK's industrial revolution took place before the modern era of GDP accounting). Crucially, they are not and were not intended to be a measure of human well-being (Agarwala *et al*., 2014a; Coyle, 2014). Rather, national accounts are human constructs, deliberately and strategically designed to tell specific stories over time. The body commissioning the accounts has considerable influence over what these stories might contain, and how the information might be used.[39] Indeed, corporate accounting

[39] Historically, accounts were developed in order to assess the taxable wealth of a territory, and the information was used to determine the prospects for war. Indeed, military interests have provided a basis for compiling accounts since at least 1085, when William the Conqueror commissioned the Domesday Book (World Bank, 2011) for precisely this reason. Nearly 600 years later, William Petty's 1665 accounts for the King of England contained the following passage:

'*the Warr cannot well be sustain'd beyond the year 1698 upon the Foot it now stands, unlesse*
1. *The Yearly Income of the Nation can be Increas'd.*
2. *Or the Yearly Expence Diminish'd.*
3. *Or a Forreign of Home Credit be Obtain'd or Establish'd.*
4. *Or the Confederacy be Inlarg'd.*
5. *Or the State of the Warr Alter'd.*
6. *Or a General Excise, in effect Introduced.*' (Bos, 2008, p. 13)

By the 1930s, national accountants were firmly back on the war path as economists (including Nobel Laureates Simon Kuznets, James Meade and Richard Stone) were developing the basis of our current system of national accounts: initial estimates deducted government spending (e.g. on the military) from national income on the grounds that it represented a reduction in the resources available for consumption (Coyle, 2014). It was only after US President Roosevelt, in preparation for the US entry into the Second World War demanded a set of accounts that showed military expenditure having a positive effect on the economy, that government spending was considered a contribution to gross domestic product (GDP) (Coyle, 2014). Political influence over what is and is not included in the national accounts is not exclusively limited to military interests, however. For example, as recently as 2012 the Greek Government, was declined for loans from the International Monetary Fund and the European Central Bank because the country's debt to GDP ratio was too high. In response, Greece's national accountants amended their GDP calculation to incorporate estimates of the informal economy, effectively expanding GDP by approximately 25% and bringing the official debt to GDP ratio within acceptable limits for securing international loans.

What William the Conqueror, President Roosevelt, the Greek debt crisis and the Forestry Commission (and indeed UK government more broadly) have in common is that the national accounts are and can be strategically designed to convey whatever information is desirable and deemed relevant for decision-making at the time. Historically, this has not included natural capital, nor has it included FEGS.

standards have a specific term for this, materiality, where information is deemed material if omitting it or misstating it could influence decisions that users make.[40] Thus, if information about natural capital could influence end-users' decisions, it would be considered material. Apart from tradition, there is no fundamental reason that national accounting procedures cannot be amended to incorporate the value of natural capital, or indeed the value of the FEGS it generates. This is not to say that national accounts are entirely arbitrary. Indeed, there are multiple accounting standards and reference manuals governing how national accounts are compiled. The two most important for the UK are the System of National Accounts 2008 (SNA, 2008; 722 pages), which is globally recognised, and, for EU countries, the European System of National Accounts 2010 (ESA, 2010; 688 pages). An additional reference, Lequiller and Blades (2014; 520 pages) serves as a guide to understanding the national accounts and usefully, the OECD compiles a further reference for capital accounting (OECD, 2009). The ESA (2010) is consistent with SNA (2008), but carries additional influence in that its implementation is required by EU regulations. This broad suite of national accounting resources contains a number of pragmatic and simplifying assumptions in order to bridge the gap between the data that would be most 'theoretically correct' and the data that may be most reliably and reasonably collected.

Together, these thousands of pages of guides and manuals provide a reasonably consistent basis for collecting and reporting a wealth of information about modern economies, but collectively they fail to adequately describe the myriad interactions and dependencies that exist between economies and the natural environment. Their most familiar measure is of course gross domestic product (GDP), where product refers to the volume of production in a given year (and is therefore a flow rather than a stock measure), domestic refers to activity taking place within a country's economic territory, and gross means that it reflects the sum value, making no explicit adjustment for capital depreciation (e.g. due to ageing infrastructure, collapsing fisheries or diminished forest stocks). As a flow measure, there is an economic case for considering whether and how to incorporate the value of environmental flows (FEGS) into the GDP calculation. It is worth reiterating however, that this would entail valuing FEGS rather than assets, and is strictly speaking an exercise distinct from natural capital accounting.

Of course, GDP is just one of many measures generated by the SNA. In addition to flow measures such as GDP, the SNA includes capital accounts so that depreciation (formally, consumption of fixed capital) can be calculated, balance sheets for economic sectors can be generated, and, finally, so that capital services can be measured to analyse production and productivity (OECD, 2009). The SNA recognises the dual role of capital as both a store of wealth and a source of capital services, and offers an 'integrated and consistent approach towards capital measurement that encompasses different measures of capital stocks (gross, net and productive stock) alongside with the relevant measures of economic flows (investment, depreciation and capital services)' (OECD, 2009, p. 11). Annual changes in the stock variables provide the basis for calculating capital service flows and consumption of fixed capital, which can in turn be used to calculate net investment in capital. When the net value of capital investment is negative, we say there has been capital depreciation. Combining the value of capital depreciation (which is a flow variable) with GDP (another flow variable) yields a measure known as net domestic product (NDP). NDP is a relevant measure here because it adjusts the value of gross domestic product in order to reflect the depletion of capital that took place in order to generate the year's economic output: it shows the amount of income available subject to the constraint that there is no decline in produced capital. Here, the natural capital analogy is perhaps at its most relevant. Natural capital could be included in an economy's capital account, and net natural capital investment could be added to NDP. This would give a measure of the amount of income available in the economy subject to the constraint that there is no decline in the combined value of produced and natural capital.

Final environmental goods and services and national accounts

A crucial distinction must be made between valuing natural capital assets and valuing the flows of FEGS they generate. These are related, but not identical. In principle, the value of the capital asset is simply the net present value of these flows, which could be calculated by modelling the future supply of FEGS, valuing them using the methods described in Section 1 and, finally, discounting them to present-year currency. One challenge, however, is that many environmental valuation methods are appropriate for valuing particular quantities or levels of FEGS, such as a unit reduction in air or water pollutant concentrations, tonnes of timber, or a number of recreational visits. These can be considered 'marginal' values in that they are appropriate within a particular range of FEGS supply. Only in relatively rare cases is it appropriate to extrapolate these marginal values across large changes in the supply of FEGS (the notable exception is for valuing greenhouse gas flows). For instance, while Fiquepron, Garcia and Stenger (2013) show that on average 1 ha of new woodland generates a savings of around EUR 22 per year (in 2004 euros) on French

[40] As defined by the International Accounting Standards Board.

household water bills, it would be inappropriate to assume that 10 000 ha of existing woodland already saves domestic users EUR 220 000 per year. The point here is that valuing FEGS is not quite the same as valuing natural capital stocks. However, if we focus instead on valuing marginal changes in natural capital stocks, values for FEGS may still be considered appropriate. This is an important distinction when attempting to 'relate the environment to national accounts'.

The existing SNA provides a framework for measuring and reporting activity within an economy. As a result, those FEGS that are traded in markets are implicitly, already incorporated into measures such as GDP. However, the contribution these FEGS make to the total value of output (formally, their value added) is not attributed to the environment, but is instead implicitly attributed to other factors of production (e.g. other capital and labour inputs). This leaves two challenges:

1. How to account for non-market FEGS.
2. Attributing value added from market-traded FEGS appropriately.

With respect to the first challenge, the simultaneous desires to (i) keep the definition and calculation of GDP the same and (ii) to incorporate the value of FEGS within the GDP calculation, are incompatible. A central feature of the SNA is its production boundary, which sets out what does and does not 'count' as economic production, and therefore what is included and excluded from the national accounts. The SNA defines economic production as 'an activity carried out under the control and responsibility of an institutional unit that uses inputs of labour, capital, and goods and services to produce outputs of goods or services' (SNA, 2008, p. 97, 6.24). It clearly states that natural processes 'without any human involvement or direction [are] not production in an economic sense… the unmanaged growth of fish stocks in international water is not production, whereas the activity of fish farming is production' (SNA, 2008, p. 98, 6.24). Thus, many sources of FEGS are specifically excluded from the SNA. Incorporating them would require an expansion of the production boundary.

There is good reason to do this. It is widely regarded that current accounting practices mask important environmental–economic relationships. Indeed, much of the value generated by FEGS (e.g. from open access recreation) is produced and consumed outside the formal market economy (i.e. the SNA production boundary) and has no representation within the national accounts. Moreover, oil spills, wildfires and water pollution can all boost GDP when remediation and clean-up efforts are sufficiently costly, yet such events can degrade and deplete natural capital stocks. This suggests that it may be possible to alter the national accounts in order to better reflect environmental–economic relationships, incorporating non-market values generated by FEGS and making adjustments for defensive expenditure and natural capital depreciation. It is important to note, however, that doing so would require a change in the production boundary of the SNA. There are precedents, however. The GDP calculation has been adjusted in the past in order to incorporate a broader set of economic activities. The most recent example is the inclusion of illegal drugs and prostitution, which together contribute between GBP 7 and GBP 11 billion to UK GDP annually (Office for National Statistics, 2014). Such expansions raise the issue of how to accurately value economic transactions when they cannot be reliably observed in standard data collection exercises. In this way at least, drugs, prostitution and environmental accounting are alike: they all require an estimation of values that cannot be readily observed in market transaction data.

The second challenge mentioned above refers to correctly attributing value added to an 'environmental sector' within the SNA. In principle, values already recorded in the SNA can be disaggregated to reflect the value added at various stages along the production process. Sectoral production functions describing how various sectors (e.g. forestry, agriculture or manufacturing) actually utilise inputs could be developed to identify relative contributions to output (formally, the value added) from labour, capital and other inputs such as FEGS. These could then be used to add 'ecosystems' as a line in the value added sector of the input output tables used to construct SNA accounts (Leontief, 1970; Miller and Blair, 2009). This would not affect the total value of GDP, but rather reattribute value from sectors that consume ecosystem services as inputs to an environmental sector that generates FEGS as outputs. Of course the process is not straightforward, and the primary challenge lies in identifying production functions that can adequately identify the share of value added that should be attributed to FEGS.

The market goods and services into which forestry is an input are already accounted for elsewhere in the SNA. Some forest FEGS such as timber are traded in markets and serve as inputs in other industries (e.g. furniture and construction). These are recorded in the current SNA and attributed to the forestry sector. However, the non-market inputs such as water purification and open access recreation are excluded. In principle, production functions could be developed to identify the contribution of non-market forest services to the production of market outputs, and the corresponding share of the market value of those outputs could be reattributed to the forestry sector. Such an accounting procedure would entail 'shifting' value added from one sector to another, without actually changing the size of GDP. As such, no double counting would take place.

There is some concern that recreation values based on travel cost estimation may introduce double counting if, for instance, expenditure on hotels and transportation is counted once in the tourism and transport sectors and again when incorporating natural capital. However, this is a misguided concern. Travel cost valuation does not 'add up' expenditure on transport and tourism and reattribute it to an environmental sector, but rather uses these data in order to impute a welfare value for the FEGS in question (recreation). Just as market data on rental housing can be used to estimate the value of non-traded (i.e. owner-occupied) housing services without double counting, complementary market data can be used to estimate recreation values without double counting. The primary difference is simply that rather than referring to observable transactions for similar (substitute) market goods (as is the strategy for valuing housing stock), travel cost based recreation values are based on observable transactions for complementary market goods. This may well be an acceptable compromise for national accountants.

The value of time spent travelling to and from a recreational site is an important component of travel cost valuation and should be included when estimating the welfare value of recreation at that site. However, this is not reflected in a theoretical exchange value; theatre ticket prices are not varied according to how far the customer travels to attend a play. Similarly, economic valuation studies typically include the time spent on site. Whether this should be included within accounting studies is unclear (extending our analogy; to what extent do theatre ticket prices vary according to the length of the play?). More formally, if we consider recreation in terms of a service generated for own consumption (analogous to cooking in the home) then it would fall outside the SNA's household production boundary, which excludes 'all production of services for own final consumption' (SNA, 2008, p. 6, 1.42). This is because the production and consumption of the service are simultaneous, and the service could not be supplied to others on the market.

Types of value in the SNA (exchange vs. welfare values)

Stemming in part from the production boundary it sets out, the SNA attempts to record the values at which produced goods and services actually exchange hands. These values are known as exchange values, where economic exchanges must entail voluntary transactions between willing producers and willing consumers. This has important implications for the prospect of incorporating FEGS or natural capital into the national accounts, as the environment often generates value even in the absence of formal transactions. Formally, the:

'SNA does not attempt to determine the utility of the flows and stocks that come within its scope. Rather, it measures the current exchange value of the entries in the accounts in money terms, that is, the values at which goods, services, labour or assets are in fact exchanged or else could be exchanged for cash (currency or transferable deposits)'.
SNA (2008, p. 50, 3.118)

This clearly states that exchange values do not capture the full benefits (utility) derived by the agents participating in a transaction. Thus, while walking in an open access woodland may entail an exchange value of GBP 0, the benefits people derive from such walks may well exceed GBP 0. Sen *et al*. (2014) estimate that recreational users might be willing to pay as much as GBP 3.59 per visit to forests and woodlands in the UK. This 'extra' GBP 3.59 benefit would not be included in an exchange value. To capture the distinction adequately, we need to introduce the notion of a welfare value. Welfare values are aptly named in that they indicate the contribution of goods and services to the production of human welfare. The GBP 3.59 from Sen *et al*. (2014) is an example of a welfare value. This relates directly to the valuation of FEGS as many of the non-market valuation techniques described in Section 1 produce welfare, rather than exchange values.

Both welfare and exchange values are important, but they have different economic interpretations. Welfare values would reflect the contribution of woodlands to human welfare, regardless of their contribution to the market economy, and their use in environmental cost-benefit analyses is relatively uncontroversial. Exchange values represent the contribution of woodlands to the market economy, regardless of their impact on human welfare, and where possible should be used for national accounting. However, when considering the production and consumption of many non-market FEGS, we are referring to activities for which no directly observable market transaction (exchange) has taken place. It is therefore not possible to record an observed exchange value. Thus we will always be talking about something that is not, strictly speaking, an exchange value, and the question is really one of trying to impute a value for the good, service or asset that is as close to what the exchange value would have been if an observable market exchange had in fact taken place (see Obst, 2015).

This poses a challenge to incorporating FEGS into the national accounts: because exchange and welfare values are not identical, incorporating both into the SNA would introduce an inconsistency. The extent to which this difference should be allowed to prevent inclusion of both natural capital and FEGS in the national accounts is hotly debated. However, by now it should be clear that what we include and what we exclude from the national accounts is, and always has been, a choice based on what information is considered desirable at a particular point in time. UK policy objectives set out in the 'Natural Environment' White Paper are at least compatible with the idea that including FEGS in the national accounts is an option worth considering (HM Government, 2011). Some authors argue that given the number of adjustments already contained within the SNA, there is no strong basis for excluding FEGS simply because they are valued using welfare rather than exchange values (Agarwala *et al*., in preparation).

Although the SNA focuses on exchange values, there is precedent within the current SNA for estimating values of goods and services when there is no observed exchange value. For instance, not every house is sold every year, but national accounts must nonetheless include the value of housing services in the economy, meaning national accountants must impute values for non-traded housing services on the basis of observable transaction data for similar, traded housing services. To accomplish this, they assume a notional transaction in which homeowners effectively rent housing services to themselves and impute values for these services by examining prices of similar rental properties. While imputed values for non-traded housing services are not strictly speaking 'pure' exchange values, they are at least consistent with the SNA because they are based on observed exchanges (SNA, 2008; Lequiller and Blades, 2014; Obst, 2015). Similarly, because most produced capital (e.g. plant and equipment, heavy machinery) is not bought and sold every year, its value must also be estimated. Here, assets are typically valued at their replacement cost, with an adjustment made to reflect the degree of depreciation (wear and tear) on the machine (Obst, 2015). For pragmatic reasons, depreciation is typically calculated using an arbitrary, fixed formula rather than a detailed inspection of each piece of machinery or asset (OECD, 2009). Finally, national accountants may value some capital assets (especially non-renewable resources) at the net present value of the future flow of goods and services they generate. The main point is that the SNA already contains a number of adjustments to enable the valuation of goods, services and assets for which direct market exchange values are not available at a particular point in time.

Recent developments in natural capital accounting

Natural capital accounting has attracted considerable attention both in the UK and internationally. In 2011, the UK's 'Natural Environment' White Paper, *The natural choice: securing the value of nature* promised to place 'natural capital at the heart of Government accounting' (HM Government, 2011) and a series of papers and reports from the UK Office for National Statistics and the Natural Capital Committee (NCC) have set out guidance and provided initial examples of natural capital accounts for the UK (Khan, 2012; Khan, Greene and Hoo, 2013; NCC, 2013, 2014, 2015; Khan, Greene and Johnson, 2014; Eftec, 2015; Office for National Statistics, 2015b). Globally, the United Nations adopted the System of Environmental-Economic Accounting – Central Framework (SEEA-CF) as a UN statistical standard in 2012, and the World Bank's initiative on Wealth Accounting and the Valuation of Ecosystem Services (WAVES) is developing initial natural capital accounts for Botswana, Colombia, Costa Rica, Guatemala, Indonesia, Madagascar, Rwanda and the Philippines. Table 13.1 offers a brief overview of international progress to date. This table lists countries and

Table 13.1 Countries with established environmental accounting programmes.

Country	Assets*	Flow accounts for pollutants and materials		Environmental protection and resource management expenditures
		Physical	Monetary	
Australia	✓	✓		✓
Botswana***	✓	✓	✓	
Canada	✓	✓		✓
Colombia***		✓	✓	✓
Costa Rica***	✓	✓	✓	
EU-27**	✓	✓		✓
Guatemala***	✓	✓	✓	✓
Korea	✓	✓	✓	✓
Mexico	✓	✓	✓	✓
New Zealand	✓	✓	✓	
Norway	✓	✓		
Philippines***	✓	✓		
South Africa	✓			

Source: Adapted from Agarwala et al. (2014b) and Lange (2014).
Note: The lighter grey tick marks in the Botswana row indicate works currently in progress.
* Asset accounts in physical and monetary terms.
** EU states are required to report greenhouse gas emissions, material flow accounts and environmental protection expenditures. Accounts for water and asset accounts for oil and gas, and forests are widely implemented.
*** Pilot member of World Bank WAVES Partnership.

regions with established programmes to account for environmental assets in monetary and physical terms, physical and monetary flows of pollutants and materials, and expenditures on environmental protection.

Of these international initiatives, the most relevant to the UK is the SEEA-CF. SEEA-CF is not a set of accounts, but rather a standardised framework for countries to use in developing sets of accounts. It is intentionally modular, in that not all components need to be developed simultaneously: countries can develop SEEA-CF compatible accounts for specific elements of natural capital that may be of particular interest or for which relevant data are most readily available. In addition to the Central Framework, the SEEA also contains guidance for Experimental Ecosystem Accounting (SEEA-EEA), which is not formally a UN statistical standard, but has been endorsed by the United Nations Statistical Commission (UNSC) as international guidance.

Combined, the various components of the SEEA integrate information on water, minerals, energy, timber, fish, soil, land and ecosystems, pollution and waste, production, consumption and accumulation within a single measurement system. It specifically excludes oceans and the atmosphere (these stocks and values would be too large to be meaningful to potential users), but includes ocean fish stocks as environmental assets (where countries possess property rights due to international agreements). The SEEA contains two distinct, but complementary accounting approaches: the first focuses on the measurement of individual natural resources, cultivated biological resources and land, while the second focuses on the measurement of ecosystems. The SEEA-CF covers:

1. Physical flows of materials and energy within the economy and between the economy and the environment.
2. The stocks of environmental assets and changes in these.
3. Economic activity and transactions related to the environment. (SEEA-CF, 2012, p. 11).

SEEA-CF sets out guidance for developing physical flow accounts, physical asset accounts, monetary flow accounts and monetary stock accounts. Monetary accounts within the SEEA-CF adopt the same asset boundary as the SNA (2008), meaning that 'only those assets – including natural resources and land – that have an economic value following the valuation principles of the SNA are included' (SEEA-CF, 2012). As far as possible, the SEEA-CF adopts the same exchange price approach as set out in the SNA, but notes that for many FEGS[41] these cannot be observed (as no formal market transaction takes place). In contrast, physical accounts within the SEEA-CF adopt a broader asset boundary, encompassing all natural resources and land within an economic territory (not just those with economic value recognised in the SNA).

Whereas the SEEA-CF measures 'individual environmental assets' (e.g. timber resources, land, mineral and energy resources, and water resources), the SEEA-EEA considers ecosystems defined as 'a dynamic complex of plant, animal and micro-organism communities and their non-living environment interacting as a functional unit'. Because not all FEGS are parts of ecosystems (e.g. minerals and fossil fuels), both the SEEA-CF and SEEA-EEA are needed to ensure the full range of FEGS is appropriately accounted.

Within the SEEA-EEA, forest ecosystems can be accounted for in terms of their spatial extent and ecological condition, or in terms of expected ecosystem service flows (Khan, Powell and Harwood, 2011; SEEA-EEA, 2014; Eftec, 2015). The first approach – accounting for an ecosystem as a whole – has obvious benefits in that it helps capture the systemic nature of environmental service provision. However, this should not be confused with accounting for specific elements of an ecosystem such as trees or water.

Based on the National Forest Inventory for Great Britain, Eftec (2015) presents a set of woodland ecosystem accounts that is consistent with the SEEA-EEA guidance. Table 13.2 presents a physical ecosystem stock account for 2012, containing estimated total extent of woodland, extent of broadleaved and coniferous species, timber volumes (by species and age), biomass (measured in terms of estimated oven dry biomass), carbon biomass stock, extent of woodland under Site of Special Scientific Interest (SSSI) designation and area of woodland in flood risk zones.

Table 13.3 shows aggregate data on estimated physical flows of ecosystem services generated by British woodland. The table also shows the estimated number of recreational visits to British woodland, based on Sen *et al*. (2014).

Table 13.4 shows estimated monetary values for these stocks and flows. Using a willingness to pay of GBP 3.47 per person per trip (based on Sen *et al*., 2012), it shows that estimated recreation values (GBP 1.7 billion, annually) dominate, as is consistent with other studies (Bateman *et al*., 2014).

[41] Note: the SNA and SEEA systems do not adopt the terminology (e.g. FEGS) set out in Section 1 and used throughout this report.

Table 13.2 Physical stock account of ecosystem condition and extent at close of accounting period 2012 (Source: Eftec, 2015).

Ecosystem: woodland	Ecosystem extent	Characteristics of ecosystem condition														
	Total area	Species type				Age (years)				Biomass stock	Carbon stock		Woodland in flood risk areas			Woodland SSSI
		Broadleaved	Coniferous	Broadleaved	Coniferous	0–40	41–60	61–80	>80		Biomass	Soil	FZ1	FZ2	FZ3	
	(million hectares)	Extent (million hectares)		Volume (million m^3)		Age by volume (million m^3)				Million tonnes (Mt) oven dry	$MtCO_2$		Extent (million hectares)			Extent (million hectares)
Coverage (countries/ regions)	GB	GB		GB		GB				GB	GB		E&W	E&W	E&W	GB
Closing stock	2.78	1.27	1.51	239	375	163	251	105	109	426	780	133	-	-	-	0.243

Note: DECC (2014) non-traded carbon price projections starting with £GBP 56.78/ per tCO_2e for 2012, are used to estimate annual carbon sequestration services. Timber unit values of £GBP 14.74/ per m^3 (broadleaved) and £GBP 14.03/ per m^3 (coniferous) are used to value annual flows.

Table 13.3 Physical flow account of ecosystem services provided by British woodland in 2012 (Source: Eftec, 2015).

		Flow (annual, 2012)		Expected future flows (20 years)	
		Broadleaved	Coniferous	Broadleaved	Coniferous
Provisioning	Biomass for timber	-	-	-	-
	Forestry Commission estimates	0.587 million m^3 (overbark)	11.78 million m^3 (overbark)	11.74 million m^3 (20 years, 2012–2031)	235.60 million m^3 (2012–2031)
Regulating	Carbon sequestration	6.01 $MtCO_2$	6.55 $MtCO_2$	120.20 $MtCO_2$	131.00 $MtCO_2$
	Forestry Commission estimates	10.3 $MtCO_2$ (2010)		-	
	Water flow regulation	Difficult to measure in physical terms		Difficult to measure in physical terms	
Cultural	Recreation	481 million visitors		9620 million visitors (2010–2029)	

Note: Some of the aggregate estimates provided in the table differ from those published by the Forestry Commission either due to limitations in replicating Forestry Commission adjustments to National Forest Inventory estimates or due to the use of a more appropriate methodology.

Table 13.4 Monetary stock and flow account for British woodland (Source: Eftec, 2015).

		Type of ecosystem service					
		Biomass for timber		Carbon		Recreation	Water regulation
		Broadleaved	Coniferous	Broadleaved	Coniferous		
Value (£GBP million)	Flow (annual)	9	165	341	372	1669 (2010)	Not modelled
	Stock (present value of future flows over 20 years)	127	2431	5738	6254	24 552	Not modelled

Current debates in natural capital accounting in relation to woodland

Accounting for woodland assets and related flows of ecosystem goods and services raises many of the same challenges encountered when accounting for other components of natural capital. However, the unique functions and characteristics of forest and woodland assets, the way they are managed and the types of services they provide mean that special consideration is required in a number of areas. These include:

- **Addressing spatial dimensions of woodland assets**: In most instances, accounting systems do not need to incorporate a high degree of spatial detail. For instance, the System of National Accounts (SNA) records the same value for the sale of a chocolate bar whether that transaction takes place in London or Manchester. However, the market and non-market value of services generated by forests and woodlands can vary substantially over distances as small as 1 km. Spatial configuration, connectivity, overlap with other ecosystems and natural capital assets (e.g. lakes and rivers), and distance from human populations are important determinants of the value generated by woodland assets. Location and spatial configuration determine the provision of flood defence services, connectivity has implications for wildlife habitats and susceptibility to pests and diseases, overlap with lakes and rivers has implications for the supply of water purification services, and distance from human populations impacts recreation values. Depending on the intended policy uses of woodland natural capital accounts, some or all of these spatial dimensions may need to be included.[42]

[42] The SEEA-EEA (2014) identifies three scales of analysis for ecosystem accounting:
1. Basic spatial units (BSUs): tessellations (grid squares) of for example 1 km^2 or cadastres (land polygons of varying shapes reflecting things such as ownership)
2. Land cover/ecosystem functional units: a contiguous set of BSUs constituting a particular type of land use or ecosystem.
3. Ecosystem accounting unit: a larger scale/fixed area taking account of natural features (e.g. topography and river catchments) and/or administrative units and boundaries (e.g. national parks).
See also Eftec (2015).

- The importance of mapping and physical accounting: Closely related to the spatial dimensions mentioned above, accurate biophysical data are crucial for identifying and understanding trends in ecological function, for designing management responses and for assessing the impact of environmental and policy change. Moreover, they are a necessary first step for developing monetary natural capital accounts. One key issue, also related to spatial dimensions, is the scale at which maps and biophysical data are collected and organised. Depending on who is developing the accounts, and for what purposes, appropriate scales might include watersheds and river catchments, land-use categories, or administrative boundaries.
- Estimating marginal vs. stock values: Most environmental valuation methods are designed to estimate the value of small (marginal) changes rather than large (stock) changes. This is appropriate for most decision-making purposes (including project appraisal and investment decisions), where for example it may be necessary to value the likely impact of afforesting or deforesting a specific unit of land without having a significant effect on the country's total woodland stock. The values estimated in such instances are marginal in that they represent a relatively small change when compared to the UK's total stock of woodland. However, those marginal values are unlikely to remain constant when we consider large-scale changes in the stock, where increasing scarcity rents and threshold effects may need to be incorporated.
- Accounting over long timescales: Compared to most produced and even other natural capital assets, forests and woodlands take a long time to mature, with rotation periods (from planting to felling) for some species reaching 150 years. This poses challenges for valuing capital assets because important factors such as discount rates, future prices and technological change are difficult to assess over the very long run.
- Ecological tipping points, resilience and functional redundancies: One of the greatest obstacles to valuing forest assets is our incomplete scientific understanding of ecosystem resilience, the existence, location and severity of threshold effects, and the extent to which functional redundancies exist within an ecosystem. Over time, improved scientific understanding and new data collection may provide useful insight. However, until then, risk registers based on existing information (Mace *et al*., 2015) may assist in identifying trends, defining meaningful metrics to describe asset–benefit relationships, and identify assets under the greatest pressure.

14. Prioritising the gaps

Alongside gaps in the underpinning natural science base, we find a significant requirement to improve, standardise and integrate evidence regarding the value of the multiple benefits delivered by trees and woodlands.

The results of the scoping study revealed a number of general critical research gaps which cut across several, if not all, of the research areas:

- Biophysical pathways: The scoping study explored both the existing biophysical literature and the valuation literature. Although we were generally able to find separate evidence relating to both biophysical processes and values, the usefulness of these existing studies is severely hindered by the absence of rigorous evidence linking the biophysical processes associated with trees to quantifiable changes in the provision of goods and services.
- Valuation literature: The existing literature is patchy, incomplete and uses a plethora of different units, years and scales. This makes a coherent approach to valuation extremely difficult, particularly because study design plays a large role in determining the valuation estimates. An integrated, consistent and comprehensive approach to valuing all of the benefits and costs associated with tree and woodland land use and management is needed.
- Making the most of existing data: There is an abundance of existing but fragmented data relating to social and environmental benefits. With advances in computing power and cross-disciplinary collaborations there is clear potential for these data sources to be brought together and used to develop sophisticated models for valuation. In order to achieve this, decision-makers will require access to the broad range of data available. In this vein, a new class of integrated ecosystem service mapping tools is beginning to emerge, including InVEST, LUCI, MIMES and The Integrated Model (TIM, developed by CSERGE). These tools incorporate biophysical models to reflect interactions between multiple ecosystem services at various spatial and temporal scales.
- Accessible decision support tools: There is a general need for the development of up-to-date, easy to use decision support tools. These tools need to be technically sophisticated enough to incorporate the most recent advances in data, methods and modelling, yet also amenable to use by non-analyst decision-makers following relatively brief (e.g. one week) training.

The scoping study also allowed the identification of knowledge gaps specific to each benefit valuation area. Based on the results of the scoping study and discussions with the steering group, these research gaps were compared in terms of the availability of existing evidence and the availability of workable solutions, expectations over the size of the related benefits (or costs) and the relevance of the topic for decision-making and policy. The research gaps were then divided into three categories to reflect whether they are (i) high priority, (ii) medium priority or (iii) long-term priority research areas.

High priorities

Water quality

- Biophysical pathways: Many valuation studies fail to link water quality outcomes to woodland management or planting actions. This makes it difficult to establish causality and limits the usefulness of existing studies for investment appraisal when the objective is to achieve specific improvements in water quality.
- Multi-impact, multi-scale valuation: There is a need to extend the valuation of different pollutants and their removal from waterways. This needs to be flexible in terms of the scale of analyses, embracing both catchment and national levels.

Water availability and flood alleviation

- Biophysical pathways: There exists a variety of evidence on the biophysical relationships between tree cover and water quantity (e.g. through modelling studies and to a much lesser degree through observed data at the catchment level). To fully quantify the effect of afforestation or deforestation data are needed to validate models, especially at the catchment scale. The absence of robust biophysical evidence quantifying the relationship between local woodland management, location and forest design, and changes in the quantity of water available constitutes a significant barrier to reliable valuation and decision-making, particularly as scale increases. There is also a gap in the evidence base in terms of the impact of climate change and rising CO_2 levels on the water use of trees, which will affect the services (dis-services) provided in the future.
- Flood alleviation: The current literature linking trees and woodlands to the prevention of flooding is growing and a relationship between them has been established. However, due to the wide variety of other factors involved in flood events, we are still some way off being able to fully quantify the effect of upstream tree planting or woodland management changes on the probability of downstream flooding.

- **Integrated valuation of water**: There is a clear need to integrate the variety of values associated with water resources and the role that woodlands can play in enhancing these.
- **Economic valuation**: Evidence on the economic valuation of changes in water quantity associated with woodlands is lacking for a variety of beneficiaries. Key business interests such as manufacturing and industrial production, agriculture and the energy sector are all potential beneficiaries for whom values are not robustly known.

Air quality

- **Valuation and spatial proximity to populations**: The health impacts caused by air pollution depend upon the number of people being exposed; a tonne of SO_2 in a densely populated area causes more damage than a tonne in a sparsely populated area. The value of pollution absorption by trees should reflect this population exposure.

Climate

- No high priority research gaps were identified for climate. Please see medium and long-term priorities.

Recreation

- **Decision support tools**: Research has the potential to substantially improve decision-making in this area. Improved decision-making tools are needed to support urban planning and the management of recreational sites.

Physical and mental health

- **Measurement challenges**: There is no commonly applied generic measure for mental health. This makes comparison between biophysical studies difficult and the lack of a well-defined and commonly understood mental health good or service poses a challenge for valuation. A more fundamental challenge is the need to establish causality, substitution and response behaviours between trees/woodland (as opposed to other environments) and mental and physical health. So, for example, if new woodlands generate visits, to what extent are these genuinely additional visits as opposed to substitution away from other activities? To what extent are there net health gains? Does enhanced engagement with nature generate positive or negative co-impacts? (e.g. does outdoor exercise stimulate improved mood or give individuals a perceived licence to indulge in other unhealthy lifestyles).

Biodiversity

- **Economic valuation**: The need for improvements in the economic valuation of biodiversity needs to be matched by better data and natural science understanding of the physical impacts of afforestation upon measures of biodiversity. In both the UK NEA and UK NEAFO analyses biodiversity was assessed through bird species indices. This approach was adopted due to the relatively poor cross-sectional and time-series data available for wider measures of biodiversity, a factor which marks out a significant research gap for future assessments. Similarly, understanding of the relationships between woodland biodiversity and human health requires more accurate and quantified assessment of the underpinning physical pathways of effect than is currently available. A particular problem arises regarding estimation of the non-use benefits of biodiversity where the lack of behavioural action precludes the use of revealed preference methods.

Trees and woodlands on farms

- There are gaps in understanding the biophysical links between trees and woodlands and agricultural output, in particular spatial and temporal differences as well as the relative merits of different species and management practices. For example:
  - Understanding the importance of the species, age and location of trees on farms for the provision of soil stabilisation, particularly in the context of an increase in the frequency of extreme weather events due to climate change.
  - Research on the importance of habitat configuration and connectivity to support biodiversity, and conversely to reduce risks from pests.
  - A deeper understanding of the relationship between different species and management practices, different pollinators and their combined impact on agricultural yields.

Plant (tree) health

- **Biophysical pathways**: The evidence base on the impact of tree health on the value of the benefits provided by trees and woodlands is small but emerging. There remains a substantial need for research in this area, in particular to address difficulties in understanding the counterfactual – what would have happened if the trees were healthy?

Urban trees

Health values

- **Biophysical pathways**: The key challenge in valuing the physical and mental health benefits provided by urban trees and woodlands lies in developing a clear understanding of the biophysical processes at work.

- Biophysical pathways: Evidence on the mental health benefits provided by trees and woodlands is undergoing substantial but slow development. A major challenge in this area is presented by the need for a common generic and comparable metric for measuring mental health. In addition, the existing evidence is often highly localised and difficult to interpret without a suitable control study. A major gap in this area is the development of rigorous, generalisable and comparable studies of the biophysical processes.
- Health Economic Assessment Tool (HEAT): This tool is available from the World Health Organization Regional Office for Europe. HEAT provides values for the benefits derived from habitual walking and cycling as recreational activities using the UK Value of Statistical Life discounted using a default discount rate of 5%.[43] However, the tool does not disaggregate the benefits by particular types of green infrastructure. As a result, reporting the total value will overstate the benefits from urban trees and woodlands, or alternatively scaling for the proportion of total green infrastructure that is trees and woodland makes the assumption that green infrastructure is perfectly substitutable.

Recreation

- Economic valuation: Values associated with recreation need to be broken down to reveal differences in willingness to pay for different recreational users (e.g. joggers, cyclists, fishermen/women and hunters).

Biodiversity

- Biophysical pathways: Johnston, Nail and James (2011) discuss the debate among urban forest professionals regarding the role of exotic versus native tree species and their contribution to urban biodiversity in Britain. They assess the current evidence and conclude that an automatic preference for native species cannot be justified, biodiversity and the wide range of services provided will be restricted by just selecting from the few native species that thrive in urban environments.
- Biophysical pathways: Croci *et al*. (2008) suggest that effective management of urban woodlands could be a good option for promoting biodiversity in towns, and Davies *et al*. (2009) and Cameron *et al*. (2012) suggest that domestic gardens also provide an important contribution to UK biodiversity habitat and hence conservation. What is important in management and new planting decisions is a scientific understanding of the roles of particular species and the complex interactions in urban ecosystems.

[43] Users are able to override this default value, and we recommend using the official UK Treasury procedure for discounting.

Issues arising from gains and losses

- Issues related to valuing gains and losses have been categorised as medium and long-term priorities.

Integrated modelling and valuation

- Perhaps the most fundamental research gap concerns the need to integrate natural science, economic and social science understanding of the multiple net benefits provided by changes in the extent and management of trees and woodlands in the UK. The current incomplete and fragmented science and valuation literature suggests that the diversity and integrated nature of woodland benefits leads to their systematic under-reporting. This in turn is likely to result in under-investment and substantial foregone values. A comprehensive extension to our understanding of these issues is therefore a significant priority for decision support.

Natural capital accounting

- The importance of mapping and physical accounting: Closely related to the need for spatial data and analysis, accurate biophysical data are crucial for identifying and understanding trends in ecological function, for designing management responses, and for assessing the impact of environmental and policy change. Moreover, they are a necessary first step for developing monetary natural capital accounts. One key issue, also related to spatial dimensions, is the scale at which maps and biophysical data are collected and organised. Depending on who is developing the accounts, and for what purposes, appropriate scales might include watersheds and river catchments, land-use categories, or administrative boundaries.
- Ecological tipping points, resilience and functional redundancies: One of the greatest obstacles to valuing forest assets is our incomplete scientific understanding of ecosystem resilience, the existence, location and severity of threshold effects, and the extent to which functional redundancies exist within an ecosystem. Over time, improved scientific understanding and new data collection may provide useful insight. However, until then, risk registers based on existing information (Mace *et al*., 2015) may assist in identifying trends, defining meaningful metrics to describe asset–benefit relationships, and identifying assets under the greatest pressure.

Medium priorities

Water quality

- Biophysical pathways and economic valuation: Most of the literature concerning trees and water quality focuses upon the impacts of new afforestation programmes rather than changes in management applied to existing woodlands (as an example of the latter see the study of preventing deforestation by Kreye, Adams and Escobedo, 2014). Additional research exploring the biophysical impact and economic values associated with changes in management are needed.

- The transfer of biophysical pathways and economic values: Once valuation functions linking woodland to water quality are established there remains a literature gap in terms of determining the most appropriate approach to transferring results across locations and time periods.

Water availability and flood alleviation

- Economic valuation: Evidence on the economic valuation of changes in water quantity associated with woodlands is lacking for a variety of beneficiaries. Key business interests such as manufacturing and industrial production, agriculture and the energy sector are all potential beneficiaries for whom values are not robustly known.

Air quality

- Biophysical pathways: Improving the natural science understanding of pollutant absorption and deposition in urban forests. This would help to reduce the large variance in monetary estimates identified in the literature.

Climate

- Biophysical pathways: Estimating the effect of trees on urban heat islands (through shading and evapotranspiration) in UK cities.

Recreation

- Economic valuation: A greater understanding and modelling of the contextual drivers of recreational demand, including weather, are needed.

Physical health

- There is some existing evidence on the physical health benefits provided by trees and woodlands; there are studies linking greenspace to exercise and physical health, and evidence of links between trees and water quality, air quality and climate (see Section 4 for further details). The challenge in this area is to understand whether these relationships hold, or are augmented, for urban trees as a subset of greenspace.
- Compounded values and double counting: Health is included in recreation and may form a part of values for the consumption of other goods and services by altering preferences. The health-related values are difficult to disentangle from values in the existing literature and there is a risk of double counting these values, for example if willingness to pay for recreational visits is combined with willingness to pay for health benefits associated with the use of recreational spaces.

Urban trees

Water resources

- i-Tree Eco provides a useful resource for estimating the impact of urban trees and woodlands on storm water drainage. However, since the hydrological models were developed in the USA and are closed within i-Tree Eco it is difficult to assess the transferability of the model to the UK setting.
- There is limited existing information on the relationships between urban trees and water quality, including their role in reducing sewage treatment costs and improving urban recreation. Estimates of the impact of urban trees on water resources at recreational sites and the resultant impact on the value of recreational visits could be constructed by using general biophysical studies on the impact of trees on water quality and valuing the impact of the change in water quality on recreation, taking into account the location of the recreation site (allowing for distance decay and proximity to population).
  Adopting this approach requires an implicit assumption that the biophysical process is the same in urban and rural areas, or that any important scaling factors (such as tree density, nutrient concentration, flow rates and distance from sewage works) were represented in the sampled data and have been controlled for.

Air quality

- Biophysical pathways: The literature relating urban trees to air quality suffers from the same limitations as for water resources. Although there are simulation models relating individual tree species (controlling for maturity) to air filtration (Donovan *et al*., 2005), these models are based on underlying biophysical studies which sample larger woodlands (greater than 2 ha). Moreover, there is uncertainty over the rates of absorption and deposition and there is very little discussion of whether these rates are likely to be the same in urban and rural areas (Powe and Willis, 2002, 2004).

Recreation

- Decision-making tools: Urban trees and woodlands provide opportunities for recreational experiences in an urban landscape, which is a mosaic of different land uses and in close proximity to densely populated residential and commercial areas. The evidence for recreational values from urban trees and woodlands is relatively robust (Brander and Koetse, 2011; Perino *et al*., 2014); however, none of the urban valuation tools reviewed here currently incorporate recreation into their valuation calculations.

- Economic valuation: Bateman, Abson *et al*. (2011) and Bateman, Day *et al*. (2014) show how location of recreational sites matters. A recreation site can generate a significant range in values depending on where it is located. The critical determinant of this range is, perhaps not surprisingly, proximity to significant conurbations, thus the study of recreation values in urban areas is particularly salient.
- Improved decision-making tools are needed to support urban planning and the management of recreational sites.

Gains and losses

- Economic valuation: The valuation of recreational benefits (costs) from incomplete gains (losses) presents a notable gap in the existing literature. This presents a challenge if we believe that the value of woodland recreation sites is related to the quality of trees at the site (e.g. species type, canopy size, tree density and tree health). There is little evidence to support or negate this; however, it seems possible that tree diseases with physical symptoms will affect the value of recreational visits. With the number of tree disease incidents rising (Figure 9.1), this is an area of increasing interest and concern.

Natural capital accounting

- Addressing spatial dimensions of woodland assets: In most instances, accounting systems do not need to incorporate a high degree of spatial detail. For instance, the System of National Accounts (SNA) records the same value for the sale of a chocolate bar whether that transaction takes place in London or Manchester. However, the market and non-market value of services generated by forests and woodlands can vary substantially over distances as small as 1 km. Spatial configuration, connectivity, overlap with other ecosystems and natural capital assets (e.g. lakes and rivers), and distance from human populations are important determinants of the value generated by woodland assets. Location and spatial configuration determine the provision of flood defence services, connectivity has implications for wildlife habitats and susceptibility to pests and diseases, overlap with lakes and rivers has implications for the supply of water purification services, and distance from human populations impact recreation values. Depending on the intended policy uses of woodland natural capital accounts, some or all of these spatial dimensions may need to be included.[44]
- Estimating marginal vs. stock values: Most environmental valuation methods are designed to estimate the value of small (marginal) changes rather than large (stock) changes. This is appropriate for most decision-making purposes (including project appraisal and investment decisions), where for example it may be necessary to value the likely impact of afforesting or deforesting a specific unit of land without having a significant effect on the country's total woodland stock. The values estimated in such instances are marginal in that they represent a relatively small change when compared to the UK's total stock of woodland. However, those marginal values are unlikely to remain constant when we consider large-scale changes in the stock, where increasing scarcity rents and threshold effects may need to be incorporated.

Long-term priorities

Water quality

- There is a gap in the literature with respect to explicit valuation of sediment impacts, acidity and turbidity in the UK, although various studies appraise the overall benefits of woodland-related water quality changes.
- Reliable, representative data on treatment costs faced by water companies across Great Britain are essential to understanding the benefits of water quality improvements. This would require detailed treatment cost data, information on upstream land use and catchment management (spatial configuration of forested areas) and sedimentation rates.

Water availability and flood alleviation

- There exists a variety of evidence on the biophysical relationships between tree cover and water quantity (e.g. through modelling studies and to a much lesser degree through observed data at the catchment level). To fully quantify the effect of afforestation or deforestation data are needed to validate models, especially at the catchment scale. The absence of robust biophysical evidence quantifying the relationship between local woodland management, location and forest design, and changes in the quantity of water available constitutes a significant barrier to reliable valuation and decision-making,

[44] The SEEA-EEA (2014) identifies three scales of analysis for ecosystem accounting:
Basic spatial units (BSUs): tessellations (grid squares) of for example 1 km^2 or cadastres (land polygons of varying shapes reflecting things such as ownership)
Land cover/ecosystem functional units: a contiguous set of BSUs constituting a particular type of land use or ecosystem.
Ecosystem accounting unit: a larger scale/fixed area taking account of natural features (e.g. topography and river catchments) and/or administrative units and boundaries (e.g. national parks).
See also Eftec (2015).

particularly as scale increases. There is also a gap in the evidence base in terms of the impact of climate change and rising CO_2 levels on the water use of trees, which will affect the services (dis-services) provided in the future.

Air quality

- Moving away from a reliance upon unit values towards an approach which relates values to both the change in pollution levels and the baseline concentrations to which they are added would allow for non-constant marginal effects of pollution and reflects the changing conditions across locations.
- Consideration of the wider remit of air pollution impacts in assessing the benefits of tree-related reductions of pollution should include health benefits both directly (in terms of the avoidance of morbidity and mortality impacts) and indirectly (e.g. by generating greater potential for beneficial outdoor activity and exercise). Also the effects of reducing air pollution on avoided damage to infrastructure such as building material damage and reductions in agricultural losses should be included.

Climate

The evidence base for the climate-related benefits of urban trees and woodlands is relatively robust.

- Economic valuation: Improved estimates of the social cost of carbon/abatement costs (carbon price). This is an active area of research, but is unlikely to be resolved in the short or medium run. As such, employing UK Government carbon prices is a straightforward compromise which would allow current research efforts to focus on higher priority issues.
- Biophysical pathways: The Forestry Commission has a well-established model of carbon accounting called CARBINE (Edwards and Christie, 1981, see http://www.forestry.gov.uk/fr/infd-633dxb for further details). CARBINE estimates stocks of carbon stored in trees and released through harvesting as well as avoided greenhouse gas emissions (through the use of wood products that displace fossil fuel intensive materials) and these models can scale from individual trees to entire woodlands, taking into account a range of management practices, such as thinning and felling.
- Biophysical pathways: There is a broad literature on the biophysical processes and economic values related to urban cooling services by shade trees in the USA (Akbari, 2002; Nowak *et al*., 2010, 2012). Using data on indoor and outdoor temperature and humidity, wind speed and direction and air-conditioning cooling energy use, Akbari *et al*. (1997) show that shade trees near houses can yield seasonal cooling energy savings of approximately 30%. Given the relative temperatures and prevalence of air conditioning in North America relative to the UK, it is possible that energy savings may be lower in the UK. However, if future studies also incorporated potential health impacts (if reducing urban heat island during summer heatwaves reduced dehydration and heat stroke), the overall value of urban cooling services from trees could remain substantial.

Recreation

- Economic valuation of gains and losses: The valuation of recreational benefits (costs) from incomplete gains (losses) presents a notable gap in the existing literature. This presents a challenge if we believe that the value of woodland recreation sites is related to the quality of trees at the site (e.g. species type, canopy size, tree density and tree health). There is little evidence to support or negate this; however, it seems possible that tree diseases with physical symptoms will affect the value of recreational visits.

Physical and mental health

- Waterborne diseases: Risk of disease is likely to be an element of willingness to pay for improvements in water quality at recreational sites; however, waterborne diseases have not been studied directly in the literature surveyed in this study.

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Annex 1: Ecosystem services and economic valuation

Ecosystem services: the paradigm and its terminology

The human economy

Understanding the contribution trees and woods make to human well-being is not a straightforward undertaking. Trees and woods impact on the environment in a multitude of ways that, through a multitude of pathways, benefit a multitude of people in a multitude of ways. The ecosystems services approach provides a framework within which we can structure this complexity and organise our thinking when approaching the task of valuation.

Central to the ecosystem services approach is the idea that we can characterise the natural world as a production system; a production system akin to those that we observe in the human economy. In the human context, perhaps the most familiar production system is that organised by a firm. Put simply, a firm gathers together various inputs in order to produce one or more outputs. In the language of economics those outputs are termed 'goods and services'. Actually, economists distinguish between two forms of goods and services:

- An **intermediate good and service** is one that is sold on to another firm and acts as an input to the other firm's productive activity.
- A **final good or service** is one that is sold on to consumers, who gain welfare from its consumption.

That final point is worth reiterating. Human welfare is enhanced by the consumption of final goods and services. Intermediate goods and services do not generate welfare in and of themselves; they only contribute to the economy's ability to produce final goods and services. For example, timber, an intermediate good produced by a lumber company, is not a direct source of well-being for humans in and of itself. Along with other intermediate goods and services including skilled labour and carpentry tools, however, timber can be fabricated into a table – a final good from which humans do derive well-being.

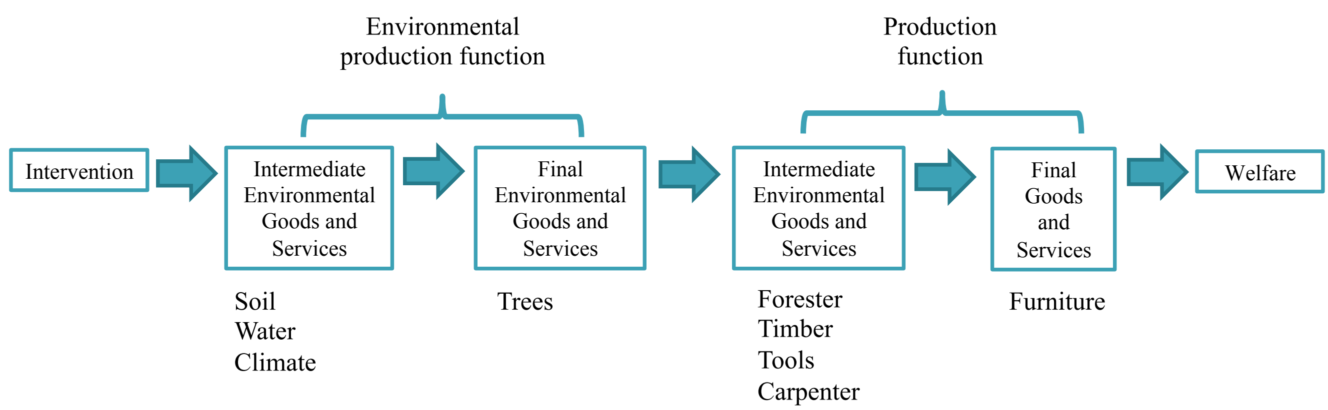
In addition to the productive activities of firms, economists recognise a second form of productive activity; that undertaken by households. The idea here is that the service flows from which households actually gain welfare are generated through individuals using their time and money to combine a particular set of final goods and services. So, for example, the benefit gained from watching a film at the cinema arises through the household combining travel, time and a cinema ticket; take any of those ingredients away from the household production process and the household gains no welfare.

Accordingly, our simple way of understanding the workings of an economy is to imagine households and firms engaged in productive activities. Those activities involve making use of a variety of goods and services in order to produce an output. The relationship between the use of inputs and the creation of outputs is described by a production function, where the term household production function is used to distinguish household productive technology from that of firms.

The natural factory

Now, the central idea behind the ecosystem services approach (Figure A1.1) is to use the same concepts in order to structure our understanding of the workings of the natural world. In a nutshell, the ecosystem services approach characterises the environment as a complex natural factory engaged in a myriad of productive processes. Of course,

Figure A1.1 The ecosystem service approach.



unlike the productive activities or firms and households, the productive processes in the environment are not organised by humans but arise spontaneously in nature; indeed that is their defining characteristic. In an exact parallel to the human economy, the productive activities of nature are described by environmental production functions. Just like their human-controlled counterparts, environmental production functions require inputs and deliver outputs. In parts of the literature, particularly outside economics, these outputs are called ecosystem services. For a number of reasons we prefer to use the more inclusive term environmental goods and services.[45]

Notice the clear distinction in this terminology between the process and the output. To be perfectly clear: environmental production functions are to flows of environmental goods and services as economic production functions are to flows of goods and services (Brown, Bergstrom, and Loomis, 2007). For example, water purification is not an environmental good/service. Rather, it is the environmental production function that delivers the environmental good/service of pure water.

Final and intermediate environmental goods and services

Another crucial distinction clarified by the ecosystem services characterisation of nature is between intermediate and final goods and services:

- Intermediate environmental goods and services (IEGS) are environmentally produced goods and services that act as inputs to some other environmental process.
- Final environmental goods and services (FEGS) are environmentally produced goods and services that enter household or firm production functions without further biophysical translation. In other words, FEGS are those particular subsets of environmental goods and services that have direct and immediate consequences for productive activities in the (human) economy.

This distinction is particularly important in the context of valuing the contribution of nature to human well-being. In particular, households and firms perceive value as resulting from the flow of FEGS that they enjoy. While the supply of those FEGS is underpinned by environmental processes that draw on a variety of IEGS, people do not have preferences for IEGS any more then they have preferences for intermediate economic goods and services. For example, people derive value from a house but would find it practically impossible to disaggregate that value into the independent contributions made by the bricks, timber and concrete that went into the production process that constructed that home. Likewise, a water company derives value from the purity of the raw water it abstracts from the environment but have no direct perception of the value of the trees, soils and biotic community that went into the environmental production process that delivered that quality of raw water.

In practical terms, the distinction between FEGS and IEGS is critical. It identifies the fact that attempts to value the environment must focus on FEGS since households and firms can meaningfully deduce the benefit they derive from those environmental goods and services. In contrast, the value derived from IEGS is not immediately apparent to households and firms. In understanding the value provided by IEGS, an extra step is required which first determines the contribution those IEGS make in terms of delivering FEGS.

The distinction between IEGS and FEGS is not always straightforward. For example, the same environmental good or service may act as an input to both human and environmental production systems. For example, pure raw water is a FEGS for water supply companies who extract it from rivers and reservoirs, but it is also an IEGS to the environmental production process through which freshwater fish reproduce (the output of which is fish that might act as a FEGS in the human activity of recreational fishing).

A further source of confusion is the fact that what some people refer to as ecosystem services actually arise from processes that are not naturally occurring; for example, food from agriculture or timber from a plantation forest. Both these goods and services result from human-organised production processes which require significant inputs of produced capital and labour on top of crucial inputs of FEGS from nature including soil, rainfall, sunshine and pollinators.

Natural capital

A complicating factor is the fact that the environment can store environmental goods and services as stocks of natural capital. Unfortunately, the term natural capital is increasingly used interchangeably with the term ecosystem services, though there are important differences between the two. Most importantly, natural capital is a stock that can persist from period to period while environmental goods and services are flows that are generated by some environmental

[45] First, environmental production functions span a range of natural processes that may be physical (e.g. coastal erosion) and chemical (e.g. low-level ozone generation) in nature as well as ecological. The emphasis placed on ecological functions by the term 'ecosystem services' is unnecessarily narrow and may cause confusion. Second, environmental production functions can result in both tangible and intangible outputs. To an economist it would seem more appropriate to refer to tangible outputs as 'goods' rather than services.

production process over a period. Of course those flows have to go somewhere; environmental goods and services are either consumed in some other production process (human or environmental) or accumulate in the form of a natural capital stock.

A further distinction that one may want to draw in this regard is between capital stocks and inventory stocks; a distinction that distinguishes between how capital is used in productive processes. In particular, the productive value of inventory is realised through liquidation but that of capital is not. Capital is undiminished in quantity or quality through its use in production. It follows that it is not the nature of the physical stock which determines whether it is capital or inventory, but the nature of the production function that exploits that stock. Indeed, the same physical stock can be both capital and inventory if it enters different production functions. For example, a stock of trees is natural capital in the environmental production function that produces habitat for wildlife (the tree stock is not diminished in the process of generating wildlife). In contrast, that same stock is natural inventory in the economic production function that harvests timber for human consumption.

The welfare implications of environmental interventions

The primary purpose of the ecosystems services paradigm is to provide a framework within which the welfare implications of an environmental intervention might be appraised. By an environmental intervention we mean any project or policy that has impacts on the natural environment. In the simplest case, such an intervention might just reduce the quantity or quality of flow of a FEGS. The task of evaluating that change is relatively straightforward; all an analyst requires is an estimate of the value that households or firms attach to that change in supply of a FEGS. How those values are established is a subject we shall return to in the next section.

More often than not, however, the impact of an environmental intervention is to perturb some environmental production process. In that case, appraisal becomes more difficult. An analyst must first turn to the natural sciences to understand how the perturbation brought about by the intervention impacts on the output of FEGS from that process. Once that relationship is established the welfare impact of the intervention can again be established by applying estimates of the value that humans attach to that change in supply of FEGS. Of course, things get more complex yet if the perturbed environmental process results in outputs of IEGS that in turn feed into other environmental production functions. In that case, analysts require even greater input from natural scientists; the welfare impacts of the intervention can only be determined by tracing the impacts of that intervention through the natural factory and establishing the resulting changes in supply of perhaps multiple FEGS.

By way of example, imagine a planned intervention looking to establish continuous cover forestry on an area of woodland previously managed as a conventional clearfelled plantation forest. That management change has a number of effects. For example, by averting clearfelling it increases the supply of the FEGS 'visual amenity', a benefit that is enjoyed by humans that take pleasure from beholding an intact forest in the landscape in which the woodland is located. In this case the relationship between intervention and FEGS is pretty much direct. We simply require a measure of the added visual amenity value of continuous cover forest when compared to clearfelling.

A more complex consequence arises from reductions in soil erosion that previously accompanied clearfelling. According to the ecosystem services paradigm, it is not the reduction in soil erosion itself that delivers welfare improvements but its consequent impacts through the natural factory on the delivery of FEGS. For example, eroded soil might be transported overland to watercourses which in turn may deposit that sediment in a downstream reservoir. In this case, the FEGS that is impacted by the intervention is the rate of deposition of sediment in the reservoir, a good (or more correctly a bad) perceived by the reservoir's managers when considering the capacity of the reservoir and their requirements for dredging. Here the analyst must establish the natural science that links continuous cover forest with reduced rates of sedimentation. The value of the intervention in this regard is the reduction in costs associated with dredging.

Economic value

Economic value: what is it?

So far we have talked rather generally about FEGS as delivering well-being to humans, and liberally used words such as welfare, value and pleasure to refer to the same thing. The essence of what is being described by these words is intuitive to all of us; having more of a FEGS makes us consider things to be, in a sense, better … given the choice, we would prefer to be in a position in which we enjoyed more of a FEGS than less. Economists often use the word utility to describe this same sense of personal preferences; if I prefer having more FEGS than less then I have more utility with those FEGS than without them.

At the heart of the economic approach to social decision-making, a field of study known as welfare economics, is the normative assertion that a project or policy should be judged on how it impacts on the utility of all members of society. Indeed, we might go further and say that that judgement should be made by comparing the sum of utilities of all members of society in the current state of the world to our predictions of the sum of utilities of all members of society after the project or policy has been implemented. Of course, to make that comparison one would not need to measure utility for every member of society, just the change in utility for everyone impacted by the project or policy. If the sum of those changes was positive then one might conclude that the project was worth pursuing. That, of course, is a highly normative assertion: there are any number of other ways one could decide whether a project or policy were worthwhile. All the same, this so-called utilitarian approach has some desirable features as a social-decision-making mechanism. For example, it is broadly democratic taking into account the preferences of everyone in society not just the elite or the concerns of special-interest groups. Moreover, unlike voting which accords each individual the same weight in the decision process, the utilitarian approach attempts to capture the different degrees of utility change that individuals might experience.

One problem remains, and it is a big one; we have no way of measuring utility. In the famous words of the Victorian economist William Jevons 'every mind is inscrutable to every other mind, and no common denominator of feeling seems to be possible'. Given that no measure of utility exists to us, economists turn to a proxy measure. The idea here is that to understand how greatly a person values an outcome (or a thing), we could measure how much of something else they would be prepared to give up to see that outcome arise. The thing that a person has to give up could be anything (e.g. quantities of their time, or quantities of socks, or chocolate biscuits), so long as the thing that is sacrificed is valuable to them. The maximum amount of that item that they would be prepared to give up is an observable measure of their utility. Of course, it would greatly help if we could use the same item for every individual since that would allow us to aggregate across individuals. Moreover, we need to choose an item that is valued by everyone and divides into fine enough units to allow accurate measurement. Not many items fit that bill. In fact, perhaps the only item that comes anywhere near is money.

A money measure of preferences for an intervention (project or policy), therefore, is defined as the maximum amount of money an individual is willing to give up in order to secure the benefits that they would enjoy if that intervention was to proceed. That measure is simply termed willingness to pay or just WTP. Of course, there may be others who stand to lose out from the intervention. A monetary measure of their preferences for that intervention is given by the minimum amount of money they would be willing to accept in compensation for those losses. That measure is termed willingness to accept or just WTA. A social-decision rule based on those measures might indicate that the project should go ahead, so long as the sum of WTPs across everyone in society exceeds the sum of WTAs.[46] These monetary measures of the change in human well-being brought about by an intervention are what economists refer to as the economic value of that intervention.

Economic value: what is it not?

Economic value is perhaps one of the poorest naming decisions ever made by economists (and there have been a few). The term simply begs for misinterpretation and is the source of endless confusion.

The first problem with the term 'economic value' is the use of the word 'economic'. In common parlance, 'economic' is associated with business and finance such that economic value tends to be misinterpreted as representing the value that accrues just to the world of commerce and not a measure capturing the well-being of every member of society.

The second problem with the term 'economic value' is the use of the word 'value'. Unfortunately, the word value has different meanings, only one of which is related to changes in well-being experienced by an individual. For example, the use of economic value is often criticised on the basis that it ignores societal or transcendental values, where the word 'value' used in that context implies the principles (held either by a society or universally) that guide us with regards to how we should behave in different situations. It is true that economic value is not a measure of moral correctness, at least not if you believe that the moral correctitude of a decision should be determined by reference to a set of independent moral standards (perhaps socially constructed or maybe prescribed by a religious text). On the other hand, one might argue that an individual's sense of the moral correctness of an intervention would be revealed by the economic value that they attached to that intervention. Moreover, the use of aggregate economic value as a means of guiding decisions is in itself the assertion of moral rule: that social decisions

[46] In fact, there is a more fundamental justification for favouring such a decision rule. In particular, if the sum of WTPs exceeds the sum of WTAs then it is possible for the government to redistribute money from the gainers in order to compensate the losers in such a way that everyone in society feels at least as well off after the intervention as before, and some feel better off. This is the so-called Potential Pareto Improvement criterion, which forms the normative foundation of welfare economics.

should serve the greater good or as Abraham Lincoln so eloquent put it 'The true rule, in determining to embrace, or reject any thing, is not whether it have any evil in it; but whether it have more of evil, than of good'.

In a similar vein, economic value has been criticised because it fails to add on separate elements that record communal values (defined as values that are enjoyed by a community rather than an individual) and other-regarding values (values derived from benefits that accrue to others). To economists, those criticisms appear ill-founded. For a start, a community is not an entity that can experience well-being independent of the humans from which it is constituted. Those humans may experience different levels of economic value as a result of being part of a community but that additional value will be captured by their own expressions of economic value. Likewise, if an individual's sense of well-being is in part determined by the well-being experienced by others then that other-regarding value will also be reflected in their expressions of economic value.

Finally, economic value has been criticised on the grounds of excluding intrinsic values; value that non-human entities hold for themselves independent of humans. That criticism is valid; economic value only considers the well-being of humans. Of course, many people regard as important the well-being of certain non-human entities (e.g. wild creatures, farm animals, pristine forest ecosystems). Interventions that impact on the well-being of those entities will in turn be reflected in the economic value expressed by those individuals. The alternative of attributing non-human entities with a value that those entities hold in and for themselves leads to such tortuous complexity that it borders on the absurd. It is possible, perhaps, to imagine that a chimpanzee might hold a sense of value for its own well-being similar to a human, less so a frog, even less so a tree. But why should being more like a human have any relevance to the value a living creature feels for itself? And then what about the values mosquitoes hold for themselves, or Japanese knotweed, or the Ebola virus? Would we have to accept that things that we don't like, that might actually do us harm, have intrinsic value that we need to respect in making social decisions? And why arbitrarily draw the line at things that are alive? What about non-living things such as rivers or beaches or mountains or the carbon in the atmosphere; do they have values for themselves? And if all or just some of these things have value for themselves how are we ever going to find out what those values are? And even if we could measure those values are we going to count them equally as those held by humans? Could the preferences of a mosquito, or perhaps a million mosquitoes, for their own well-being override those of a human?

The concept of economic value is based on the idea that value (or rather utility) is a human construct and that it provides a measure by which we might gauge what is best for a human society. It is perfectly compatible with the idea that value may come from non-human entities but only insomuch as they increase the well-being experienced by humans either by supporting our livelihoods (e.g. a human might value the soil because it enables them to grow food) or enhancing our existence (e.g. a human might value the sensory delights of wandering through an ancient woodland) or because of a sense of moral duty (e.g. some humans might value a mosquito just because they believe that every living thing has a right to live … though others might have an alternative opinion). Ultimately, things might have been a lot simpler if the measures of WTP and WTA had been given a less contentious name (perhaps, utili-money!) but for now we are stuck with the term economic value.

What determines the economic value of a FEGS?

As we have already discussed, a FEGS is an environmental good or service produced by some environmental production function whose value is directly perceptible to a human without that FEGS undergoing any further biophysical translation. Of course, it would be wrong to think of a FEGS as being some simple homogeneous good delivered in neat units, as per cans of baked beans or loaves of bread. Indeed, more often than not FEGS are more akin to complex differentiated goods like cars or houses whose value to a human is determined by the array of quality characteristics that define its attributes. Accordingly, in order to determine the value a FEGS can deliver one must first establish the important quality dimensions of that FEGS. We describe these as the attributes of the FEGS.

As an example, consider the FEGS the 'woodland environment'. A woodland environment might, for example, deliver value by providing the location in which an individual undertakes outdoor recreation. The value derived from that recreational experience will be determined, in part, by the woodland's attributes; for example, its extent, the species and age structure of the trees, or the chances of encountering different forms of wild flora and fauna. More formally, we think of those attributes as being the dimensions of quality that are determined by the environmental production process which delivers a woodland environment.

Of course, the value a FEGS delivers to an individual is not solely determined by the levels of its attributes. Rather the context in which a FEGS is enjoyed (or as economists would say, consumed) also plays a major part in determining how much value that FEGS delivers to an individual. To be more formal once again, we think of a FEGS as being an input to a human production function (be that a household's production function or a firm's production function) and it is this production function that generates flows of value. To continue our example, the woodland environment enters the household production function through which an individual generates recreation experience. Of course, the woodland environment is just one argument in this function. In addition, the function will include a series of other FEGS that act as complements or substitutes for the woodland. An example of a complementary FEGS might be a river that runs through the woodland (the output of a hydrological production function). An example of a substitute might be a beach or a lake which represents alternative natural environments in which an individual might spend recreational time. Moreover, human-produced final goods and services (FGS) will be important arguments in the recreation production function. For example, the woodland might have paths or a visitor centre that enhance the value provided by the woodland environment. Likewise, the household might need to purchase other FGS such as transport, fuel, recreational equipment or accommodation in order to enable or enhance the production of recreation value flows. As we shall see shortly, observing these purchases of marketed FGS provides one means by which we might estimate the value flow individuals derive from a FEGS. Finally, the value an individual derives from the FEGS and FGS that enter the household production function will be qualified by their own personal circumstances. For example, gender, age and income may shape the value flow that an individual derives from a FEGS.

To summarise, the value flow from a FEGS is determined by at least two things:

- The FEGS's attributes, as determined by the environmental production function through which it is delivered.
- The context within which the FEGS is consumed, as determined by the other FEGS, FGS and qualifiers that enter the human production function through which the FEGS delivers value.

One final issue must be addressed in determining the economic value of a FEGS: aggregation. To determine the total economic value emanating from a FEGS, we need to add together the value flows accruing to all the individuals who gain benefit from that FEGS. Clearly that is not always an easy task, particularly as the context within which individuals consume a particular FEGS will differ, perhaps markedly, across individuals. Continuing our example, the proximity of a woodland used for recreation will differ across individuals, changing the costs they must incur in accessing that woodland and the proximity of other natural areas offering substitute locations for outdoor recreation.

Types of value

Without a doubt, environmental goods and services deliver value flows in numerous ways. As we have already seen, a woodland environment can deliver value through enhancing the visual amenity of a landscape, by providing the setting within which recreational activities are enjoyed and perhaps simply through the knowledge that that woodland environment provides a refuge within which wildlife can thrive. In the terminology of the ecosystem services framework, the woodland is an argument in the household production functions that respectively generate value from the visual amenity of the landscape, recreational experiences and the existence of wild places. Moreover we have seen that woodlands can also deliver value through indirect routes in which they are IEGS that feed into environmental production functions. Examples of the latter include the role of woodlands in mediating water quality, soil erosion, flooding and air quality.

This seeming complexity has led to various attempts to categorise value flows from environmental goods and services. Over the years, numerous different types of value flow have been identified including direct use values, indirect use values, non-use values, option values, bequest values, existence values, altruistic values, and so on. To a certain extent those attempts at categorisation are superseded by the ecosystem services approach's focus on environmental goods and services as arguments in human production functions. In short, an environmental good or service generates as many different values as there are human production functions to which it contributes. While categorising these and giving those categories names is an interesting academic exercise, and reminds us of the range of ways in which value flows from the natural environment, it provides little further guidance as to how we should go about measuring those value flows.

Having said that, perhaps one or two important distinctions are still relevant; for example, the distinction between indirect and direct values. Actually that distinction maps perfectly on to our now (hopefully) familiar distinction between IEGS and FEGS. In other words, an environmental good or service generates direct value if it enters a human production function as a FEGS, but indirect value if it contributes, through some biophysical process in an environmental production function, to the supply of some other FEGS. The distinction is important because it informs us as to when we can value an environmental good or service directly (as a FEGS) as compared to when we first have to understand the science of the biophysical process by which it contributes (as an IEGS) to the production of FEGS.

A second distinction in values that is also of importance is that between use and non-use values. Traditionally that distinction has been characterised as being the difference between a value that is derived from physical interaction with a FEGS (use value) and one in which value is derived without physical proximity to or interaction with a FEGS (non-use value). While a distinction based on interaction is, of course, possible, increasingly it has been seen as uninformative with regards to measuring economic values.

As we shall see in the Section 3, there are fundamentally two ways in which economic values might be estimated. First, values might be revealed to us by observing actual behaviour (usually with respect to the purchase of a market good) that is somehow related to the values gained from a FEGS. Such methods are termed revealed preference approaches to valuation. Second, we may simply go and ask people how much value they derive from a FEGS; a set of techniques termed stated preference approaches to valuation. The problem with distinguishing between use and non-use values on the basis of physical interaction is that such a distinction does not neatly map onto the application of revealed and stated preference methods. For example, consider a person who gains value from a woodland as an incidental part of their daily routine; for example, from seeing that habitat while sitting on the bus on the way into work. There is little doubt that such values are derived from use, but that value leaves no signature in their market behaviour; they would pay their bus fare with or without the woodland. Likewise, consider the individual who values a woodland not because they currently use that resource, but because they expect that they might wish to make use of it in the future. Whether this is a use or non-use value is not at all clear. The only thing that is clear is that this value cannot be estimated by observing their current market behaviour.

Accordingly, distinguishing between values as emanating from the use or non-use of an environmental good or service is neither particularly helpful nor particularly relevant. Rather the fundamental distinction that analysts must make is between values that can be estimated from observable behaviour in markets and those that cannot. If changes in the flow of a FEGS results in observable changes in market behaviour then values can be estimated using revealed preference methods. In the absence of a behavioural response in markets, values must be estimated using stated preference methods. With that said, since the terminology of use values and non-use values has become so engrained in the literature, we are actually going to continue with its application – with the caveat that what we are really referring to is a distinction between values that can be deduced from observable behaviour and those that cannot.

Prices and economic value

Not all goods, of course, are delivered to us by nature. Indeed, in addition to FEGS, people get value from a whole array of final goods and services (FGS) that result from human-organised productive activity. To fix ideas, let us assume that the FGS we are talking about are produced by a firm. A rather major part of the economic activity in our economy revolves around the transfer of these FGS from those that make them to those that want them. How that transfer is arranged differs across economies, but by far the most prolific mechanism is the one based on exchange; particularly, the exchange of money in return for a FGS.

Without wishing to bore knowledgeable readers, it is worth briefly reviewing the basic theory of exchange as envisaged by (neoclassical) economists. That theory begins by positing an individual who would like to consume a unit of some FGS produced by a firm. As we have seen, the strength of that consumer's desire for that unit of a FGS can be expressed in terms of their willingness to pay (WTP): that is, the maximum amount of money they would willingly give up to acquire that good.

The terms under which a firm might agree to supply the good to that individual will depend on the compensation they are being offered. Again, the required compensation can be measured in money terms by the firm's willingness to accept (WTA): that is, the minimum amount of money that they would accept for giving up a unit of the FGS. For a firm, we would normally imagine that that WTA amount would equate to how much it cost them to produce that unit of the FGS.

Figure A1.2 shows an example of how the WTP and WTA of the consumer and producer might compare. In this example, the WTP of the consumer exceeds the WTA of the producer such that the possibility exists for the two parties to affect a mutually advantageous exchange in which the FGS is transferred from the latter to the former in return for a money payment, p. Notice there is nothing special about the p illustrated in the diagram; exchange could take place at any price, so long as $WTA < p < WTP$.

A central concern in economics, particularly welfare economics, is to evaluate the benefits realised by these two agents from participating in the exchange. We have already seen that we can measure the economic value of individuals receiving a good through their WTP. So the benefits of this exchange are given by the consumer's WTP. But in the case of exchange of a FGS, there is also a party that loses out by giving up that FGS. The value of the firm's loss is given by their WTA. Accordingly, we can measure the net benefits of exchange as the difference between WTP and WTA. Another way to look at this measure of the economic value generated by exchange is in the form of surpluses. Referring back to Figure A1.2, that same measure of economic value can be calculated by adding together the buyer's consumer surplus (that is, the difference between their WTP and the price) and the seller's producer surplus (that is, the difference between the price and their WTA). Roughly speaking, the measures of consumer surplus and producer surplus measure how much of the economic value generated by the exchange is captured by the buyer and how much by the seller.

Perhaps the most important thing to note from the discussion so far is that the price at which the exchange takes place is neither an accurate measure of WTP or WTA or, for that matter, the economic value generated by the exchange (WTP–WTA). Prices are not economic values … though we shall qualify that shortly.

In a real economy things are made somewhat more complex by the existence of very many buyers and sellers. One way of summarising the preferences of the buyers is through a demand curve which (ignoring some technical complexities) might be thought of as the graph of WTP amounts of consumers ordered from highest to lowest from left to right (see left panel of Figure A1.3). Likewise the compensations required by sellers can be described by a supply curve: the graph of WTA amounts this time ordered from lowest to highest from left to right (see middle panel of Figure A1.3). As shown in the third panel of Figure A1.3, when placed on the same graph, the intersection of demand and supply curves reveals the quantity of goods that could potentially change hands through a process of mutually advantageous exchange, : the sellers of each of those units could be paired with a buyer whose WTP exceeds their WTA. Indeed, the quantity of economic value that might be generated in the economy through the exchange of this FGS is the sum of differences between those WTP and WTA amounts, a quantity that on the diagram is shown as the area labelled 'surplus' between the demand and supply curves up to . While highly stylised, the supply–demand diagram encapsulates the underpinning economic forces which drive non-coercive exchange in the economy.

Now with those (simplified) basics in place, let us consider how exchange might progress in a real economy. When the economy consists of very many buyers and sellers with perfect information and where none of those buyers or sellers is a sufficiently 'big player' to independently manipulate the terms of exchange, then a perfectly competitive market may evolve as the institutional setting within which exchange is affected. Perhaps the defining feature of such an institution is that all of the exchanges takes place at one particular price. As shown in the left-hand panel of Figure A1.4, that one price is determined by the intersection of the demand and supply curves,

The fact that only one price exists for the FGS, the so-called law of one price, arises from competitive pressures in the

Figure A1.2 Basic elements of exchange – WTP and WTA

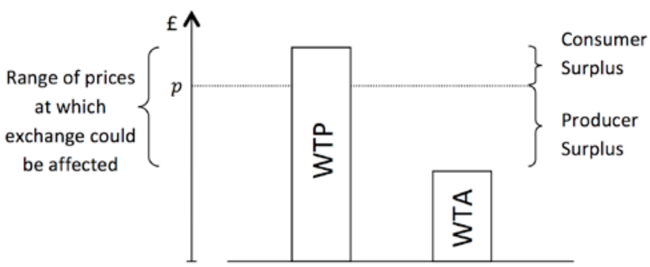


Figure A1.3 Demand and supply curves

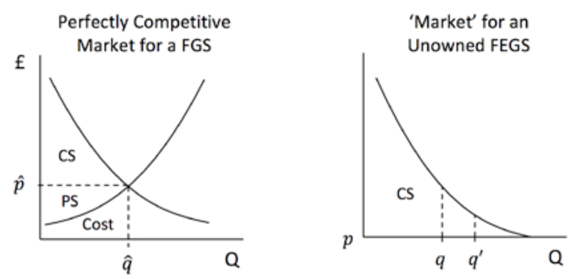
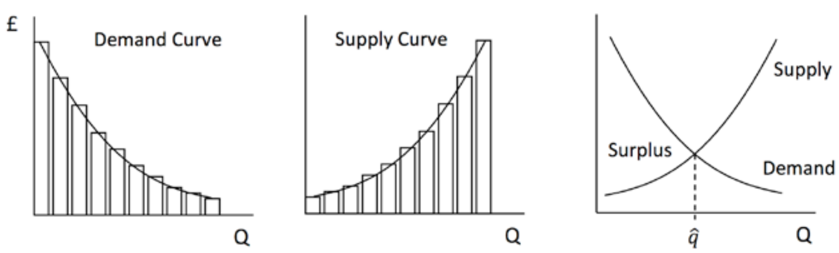


Figure A1.4 Prices and market allocation



market: attempting to sell above the market price is impossible since other producers are prepared to sell at the market price and selling below the price is irrational since it will be possible to enjoy greater surplus by selling at the market price. The fact that the perfectly competitive market price will be set at the point where supply and demand curves intersects, in Figure A1.4, also results from competition. If the price were lower than then there would be excess demand and consumers would compete with each other to get hold of the scarce FGS and so drive prices up. If the price were higher than then there would be excess supply and producers would compete with each other to sell their goods to scarce buyers, pushing the price down. At the price , supply equals demand such that the competitive pressures balance and the market is in equilibrium.

There are two important things to note about (perfectly competitive) market prices:

- First, at the price , every exchange that could take place (i.e. where WTP > WTA) does take place. Accordingly, a perfectly competitive market maximises the economic value (or surplus) that is generated by exchange. In Figure A1.4, that economic value is shown as the sum of consumer surpluses (CS) and producer surpluses (PS). It is for this reason that economists often advocate free markets as a good way to exchange FGS.
- Second, notice that not all demand is satisfied by this market exchange process. There are some people, possibly lots in a big economy, who do not get to consume the good because their WTP is just slightly below the market price . That observation is going to be true of any price, and not just one set in a perfectly competitive market. Indeed, we can use that result to help us work out the economic value that might be generated by a project or policy seeking to expand the production of a FGS. Put simply, the market price gives a good indication of the WTP of individuals in the economy for more of this FGS. Accordingly, when market prices exist for an FGS, it is a reasonable approximation to use those prices as a measure of WTP for increased supply of that FGS (from which, of course, we would have to subtract the cost of making those extra FGS to arrive at a measure of the net gain in economic value). So a project that increased the supply of timber from a managed forest would be justified in using the price of that timber as a guide to the economic value generated by each unit of increased timber production.

Finally, take a look at the right-hand panel of Figure A1.4. Here we have constructed a demand curve for a FEGS in exactly the same way we did for an FGS; just by ordering consumers WTP amounts for that FEGS from highest to lowest. Notice that because this is an unowned FEGS, there is no seller in this market and, therefore, no process of exchange whereby a price might be established. In effect the price is set at zero. Without some human-organised production, the level of FEGS is fixed by nature at an amount . When we have talked previously about valuing interventions which change the supply of a FEGS, what we have been imagining is that the quantity (or quality) of FEGS available for consumption is shifting. In Figure A1.4 that is illustrated by the new higher level of supply, . The economic value of that change can be calculated by adding up all the WTPs of those who would consume those extra FEGS; in Figure A1.4 that is just the area between and below the demand curve. Observe, that in this case we do not have market prices to guide us with respect to the WTP of individuals for this extra supply of FEGS. To estimate economic value, therefore, we need to turn to the tools of non-market valuation.

Measuring economic value

In the last section we saw that for FGS resulting from human-organised production systems, market prices often provide an easy-to-observe approximation for economic value. In this section we consider the problem of how to estimate economic value for FEGS when those environmental goods and services are not traded in their own independent market and, as a result, do not command a price.

In order to think about the possibilities for valuing FEGS, it is essential to be more explicit about how those FEGS enter human production functions. Perhaps the most fundamental distinction is between FEGS that enter firms' production functions and those that enter households' production functions. Indeed, we organise our following discussion around that dichotomy.

Non-market valuation: firms

In economics, a firm is an organisation dedicated to producing some good or service. In most cases, the purpose of that activity is to make profits, profits that are shared between the individuals who have an ownership stake in the firm. So every extra pound of profit made by a firm, is an extra pound of money received by a household somewhere in the economy. The economic value of a pound is rather easy to estimate; the maximum an individual would be willing to pay in order to receive one extra pound, is just one pound. In other words, the economic value of an intervention which changes a firm's profits can be measured simply as that change in profits. The tricky bit is finding out how a firm's profits are impacted by an intervention that changes the level of a FEGS that it enjoys.

Profit function method

In theory, given an awful lot of data and technical information it might be possible to estimate a firm's profit function which captures the relationship between the quality and quantity of FEGS enjoyed by a firm and its profits. Of course, to isolate that relationship one would need to know rather a lot about the firm's activities and technology including how much it has to pay for other inputs (intermediate FGS) and for labour. As a result, the profit function approach is rarely adopted – the data required to implement the method are often commercially sensitive and difficult to acquire.

Supply curve method

A more manageable undertaking is provided by the supply curve method. This method derives from the fact that the impact of environmental change on a firm's profits can be estimated by calculating areas between shifting supply curves for a firm's output. The supply curve method is somewhat less data intensive, relying only on establishing the relationship between output, price and environmental quality, all of which should be observable.

Input demand curve method

Changes in profits from environmental change can also be estimated by looking at shifts in demand curves for marketed inputs (intermediate FGS). For this input demand curve method to return a complete measure of profit change it must be the case that the input is essential to the production of the firm's output.

Firm value method

An alternative strategy is provided by looking at the market value of firms themselves. It is assumed that, in a competitive market, the value of a firm will reflect its expected future profits. Accordingly, differences in the value of firms that result from differences in environmental quality inform on how environmental change will impact on a firm's profits. This method has seen most application in the agricultural sector under the guise of the Ricardian technique. Here it is assumed that the profits from agricultural enterprise are completely expropriated by the owner of its underpinning factor of production: land. The price at which land sells, therefore, reflects expected future profits from agriculture. Moreover, differences in the value of land resulting from differences in environmental quality provide information on how agricultural profits might be impacted by an intervention that brought about changes in the environment.

Production function method

The production function method proceeds by estimating the technical relationship between a firm's production of output and levels of a FEGS used as an input (these relationships are also referred to as dose–response functions). Using that technical relationship, an analyst can predict how environmental change will impact on profits by multiplying the predicted change in levels of output by the market price of output. In agriculture, for example, field experiments might establish the production relationship between rainfall and crop yield. The production function method would value environmental changes that changed the incidence of rainfall by multiplying the predicted changes in crop yield by the price of those crops. The key weakness of this method is that production functions are technical relationships and not behavioural ones (like supply and factor demand curves). In reality, for example, farmers will respond to changing patterns of rainfall by planting at different times of the year, artificially irrigating or perhaps changing crops. We can reasonably assume that those behavioural adaptations will always act so as to increase profits in the changed situation. Accordingly, the production function method will overestimate profit changes that result from reductions in environmental quality and underestimate those resulting from improvements.

Defensive expenditure method

A final method that can provide bounds to the profit impacts of a change in an environmental input is the defensive expenditure method. Here economic value is approximated by estimating how the cost of producing current levels of output would change as the result of a change in supply of a FEGS. Again the method overestimates the fall in profits when environmental quality is reduced and underestimates the rise in profits when environmental quality improves because it does not allow for the behavioural response of the firm to optimally adjust levels of production under the new conditions. Of course, estimating the full behavioural response of costs and production to changes in an environmental input is the basis of the supply curve method. Accordingly, one can think of the defensive expenditure method as providing a rough approximation to the supply curve method.

Non-market valuation: households

When a FEGS is enjoyed by a household rather than a firm, there exist two basic approaches to gathering information regarding the economic value of that FEGS.

The first set of methods are described as revealed preference methods and these depend on the fact that a FEGS is often only one input that a household can or must bring together in order to produce some value stream. Using the technical language we introduced earlier, the FEGS is only one argument in the household production function. In some cases, for example, a household may need to combine the FEGS with some marketed FGS in order to enjoy the final value stream. In other cases, the household may be able to use a marketed FGS instead of the FEGS in order to produce a value stream. The key insight, however, is that we can use observations on purchases of these related FGS in order to deduce the value provided by the FEGS.

The second set of methods are those that are described as stated preference methods. In stated preference methods, individuals are directly questioned about the economic value they derive from a FEGS. As we have already discussed, stated preference methods are the only methods that allow estimation of non-use values; that is, values that leave no record in observable behaviour.

Attribute of heterogeneous market good: the hedonic price method

The first revealed preference method we discuss is known as the hedonic price method. This method is appropriate when quantities of a FEGS are bundled up as part of some other good that can be purchased in a market. By observing purchases of that market good, we can learn something about the value placed on the FEGS. The standard example is property, in which by buying a house one also purchases access to the environmental quality enjoyed at that property's location (e.g. levels of noise pollution, air pollution, views of and proximity to wooded areas).

Property is an example of a heterogeneous good, where the set of units that are traded in a market differ in terms of the levels of a number of attributes. In the case of property, that list of attributes would include not only environmental quality, but also the physical characteristics and quality of the building and the proximity of the property to local amenities. Other examples of heterogeneous goods include cars, computers and breakfast cereals.

Like any market good, the price of a heterogeneous good is determined by demand and supply pressures in a market. Unlike simple goods, however, we are unlikely to end up with one price for each of the multiple different forms of a heterogeneous good. Rather the price of a heterogeneous good can be described by what is termed a hedonic price function, a function which indicates the price at which a unit of the heterogeneous good with particular attributes will sell for in the market.

Since households prefer better environmental quality to worse, this hedonic price function will tend to be increasing in environmental quality. In other words, the price for each extra unit of environmental quality, or what in the hedonics literature is called its implicit price, is positive. The key to this form of non-market valuation is to use data on property prices to identify the implicit price of a FEGS. For the same reasons we discussed in the last section, implicit prices are a reasonable approximation for how much households are willing to pay for more of an environmental good.

Attribute of waged job: the hedonic wage method

A qualitatively different situation in which a FEGS may be bundled up with a marketed good occurs in labour markets. In particular, consumers may select employment from an array of different jobs where those jobs differ according to a variety of attributes. Of particular interest are attributes of environmental quality and of safety in the workplace.

As in the hedonic pricing method, economic theory suggests that the interaction of firms, supplying jobs with different attributes, and consumers, with different preferences for those job attributes, will lead to the establishment of a hedonic wage function that clears the labour market. Since consumers place positive value on environmental quality and workplace safety, that wage function should be decreasing in those attributes. As before, we can use that price as an approximation to economic value.

Substitute good in household production function: the defensive expenditure method

For many types of environmental quality, such as those relating to air and water pollution, it is not the pollution itself that concerns consumers but how that pollution impacts on their health.

While the level of environmental quality is out of their control, consumers can purchase other goods and services that act as substitutes for environmental quality in the production of health end points. For example, items including air filters, sun screen and bottled water have been posited as marketed substitutes for environmental quality in producing health.

That substitution relationship can be used to value a FEGS using what is often termed the defensive expenditure method. In that approach, we look for situations where we can observe how much people spend on the substitute marketed good when they experience a fall in supply of a FEGS. Intuitively, when environmental quality falls, consumers will respond through making defensive expenditures on the substitute market good. The payments they make in that offsetting will give us a lower bound estimate on the value they derived from the FEGS.

Complementary good in household production function: the travel cost and associated methods

An alternative household production relationship that may exist between a FEGS and marketed goods is one of complementarity; that is to say, the FEGS can only be enjoyed if a marketed good is purchased as well.

Here the standard example is recreational experiences in natural areas. To enjoy such a recreational experience, consumers must combine the environmental quality of the natural area with a series of complementary market goods, most notably they must pay the costs of transporting themselves to that area. Since the quality of the natural area cannot be enjoyed without the market purchases, those purchases provide information on the value households place on environmental quality. In the context of valuing the contribution of environmental quality to recreational experiences, this approach is commonly termed the travel cost method. The intuition is simple: to enjoy the recreational site I have to pay the travel costs of getting to that site. Of course, I would never pay more in the costs of travelling to that site than the value I got from visiting. Accordingly, people's expenditure on travelling to sites provides information that can be used to deduce economic value

One complexity recognised by practitioners of the travel cost method is that travelling to a recreational site uses time that a consumer could have employed undertaking other utility-raising activities. Accordingly, in nearly all applications, practitioners will add an element to the travel cost that represents the opportunity cost of time spent travelling.

A limitation of the travel cost method is that it does not extend easily to situations in which consumers are faced by an array of substitute recreational sites. In those circumstances, the consumers are as concerned with the choice between sites as the choice of the number of trips to take to one particular site. The standard method applied in the case of multiple sites is provided by the random utility model: a discrete choice modelling technique in which consumers are assumed to choose which particular site to visit based on the qualities of, and costs of travel to, the different sites available to them. The technical details of this approach are a little more involved, but the essence of the method is the same; costs incurred travelling to a recreational site tell us something about the economic value gained from spending time at that site.

Stated preference methods

In some circumstances, consumers derive value directly from a FEGS without it leaving any footprint in their observable behaviour. A standard example of such a case might be the pure existence value that a consumer derives from the ongoing existence of a species, say the blue whale, or natural habitat; say the Amazon rainforest. Such values are derived in complete isolation from marketed goods and, as such, their value to consumers cannot be inferred from market behaviour. For these goods, practitioners of non-market valuation have no option but to adopt stated preference methods.

Stated preference approaches rely on survey methods which present respondents with carefully crafted questions asking them to indicate amounts of money they would exchange for changes in the supply of a FEGS. These surveys are often described as creating a hypothetical market in which respondents can undertake imagined transactions for FEGS. Since the hypothetical market is completely constructed by the researcher, they can potentially return values for any conceivable change in provision of any FEGS.

Stated preference methods are often classified into contingent valuation methods and discrete choice experiments, though in truth there exists a continuum of related methods of which these represent extremes. In contingent valuation studies respondents are asked to consider a particular change in provision of a FEGS and presented with questions that reveal the economic value they attach to that change. In contrast, discrete choice experiments present respondents with tasks that ask them to choose between two or more options, where each option consists of a different level of supply of a FEGS and an associated cost. Analysis of respondents' choices in such an experiment reveals information on the value they attach to different levels of provision of a FEGS.

Stated preference valuation methods are not limited in their application to FEGS that just provide non-use value. Rather practitioners could just as well apply stated preference method to the valuation of any FEGS. Indeed, it is common for marketers to use stated preference techniques to explore the public's WTP before they are brought to market.

The debate about whether values from stated preference studies should be considered as being as reliable as those from revealed preference studies still rages. There is no doubt that the values derived from stated preference studies have been shown to be susceptible to manipulation through changing what might be considered irrelevant features of the hypothetical market. At the same time, the econometric gymnastics that is often needed in order to extricate value estimates from revealed preference data casts doubt over the precision of those approaches. Ultimately, many FEGS, particularly those that deliver large non-use values, are not amenable to valuation through revealed preference methods. In those cases, we have no alternative but to resort to stated preference techniques.

Methods that do not reveal economic value

As we have seen, the theoretical foundations that underpin the notion of economic value lead to the conclusion that an intervention's merits can be judged by aggregating over measures of households' WTP and WTA. Indeed, each of the methods of non-market valuation discussed above attempt to measure just those quantities. There are other methods that bear passing resemblance to the economic methods of non-market valuation but do not attempt to measure WTP or WTA. Examples of such methods include the damage cost avoided, replacement cost and substitute cost methods:

- The damage cost avoided method attempts to value the protective services offered by the environment; for example, the service a woodland provides in preventing flooding of residential areas further down a catchment. The value of that service is taken to be the value of the damages avoided because the flooding is prevented.
- The replacement cost method suggests that the value of an environmental asset and the services it provides can be estimated by calculating the cost of re-creating that environmental asset elsewhere. For example, the cost of destroying a woodland might be estimated as the cost of establishing an identical woodland in another location.
- In a similar vein, the substitute cost method measures the value of an environmental asset by calculating the cost of creating other assets that provide the same flow of services. For example, the cost of damaging a natural fish habitat and nursery might be estimated by measuring the cost of a fish breeding and stocking programme.

Observe that each of these methods uses a cost to proxy the correct measures of value based on WTP or WTA. Unfortunately, costs and values may have little in common. For example, with the substitute cost method, one might reasonably argue that WTP for an environmental good and service could never be more than how much it would cost to provide those services in some other manner. On the other hand, it is always possible that the value derived from those services is significantly less than the cost of creating a substitute. Accordingly, such methods should be used with great caution and an understanding that they may provide bounds to value but do not provide estimates of economic value itself.

Methods of value transfer

In most cases, decision-makers considering the economic value of some proposed intervention will not be in the privileged position of being able to commission an original valuation study. In such circumstances, perhaps the only way to proceed is to draw on estimates of economic value taken from previously implemented original studies.

Obviously the level of confidence that can be had in such value transfers (also known as benefits transfers) will depend on the quality of the original study. At the very least one would hope that an appropriate valuation method had been used and that the original study was based on a suitably chosen sample of a reasonable size. Even if the original study meets those standards, it is clear from our earlier discussion that the likely accuracy of a value derived from another study will be determined by two things:

- The degree to which the attributes of the FEGS in the original study resemble those of the FEGS to which those values are being applied. For example, estimates of the recreational value of establishing a new broadleaved woodland would likely be more robust if the study from which they were transferred also concerned broadleaved as opposed to coniferous forest.
- The degree to which the context in which that FEGS was consumed in the original study resembles the context of consumption in the application. For example, the flood protection value of a woodland in the upper reaches of a catchment is best approximated by a study that looked at such values for woodlands in a similar location and with similar proximity to vulnerable property.

Of course, it is highly unusual that a study will exist that provides the perfect fit in terms of both attributes and context. Indeed, the usual procedure would be to attempt to adjust values from the original study in order to account for differences in the attributes and context of the situation in which they are to be applied. Ideally, we would like for those adjustments to be driven by empirical evidence perhaps in the form of a transfer function; that is to say, a function that indicates the relationship between levels of value and different levels of attributes and context.

In some cases, the data underpinning a primary study may have exhibited sufficient variation in FEGS attributes and/or context that the original analysts were able to estimate and publish a transfer function. It is frequently the case, for example, that studies will examine how proximity to the location of supply of a FEGS (say a nature reserve) impacts on how much value it delivers to households. Such relationships are described as value distance decay functions. Likewise many studies will examine the relationship between household income and value. Again, such relationships can be used to adjust values to better reflect the characteristics of the situation to which those values are to be applied.

A second approach to developing transfer functions is provided by the method of meta-analysis. Meta-analysis is a statistical approach in which valuations drawn from multiple original studies are combined and analysed in order to identify how estimates differ as a result of differences in the attributes of the FEGS being valued and differences in the context in which that FEGS was consumed. Meta-analyses will often also examine whether the values differ systematically according to the valuation method used in the original studies and/or differences in the methods of data collection and analysis.

Aggregating values over people, time and space

Whether taking values from an original study based on a sample, or transferring them from previous studies, a final step in estimating the economic value of an intervention that impacts on the supply of a FEGS is that of aggregation. To arrive at a total social value, we must add up the value changes experienced by each individual impacted by the intervention, wherever and whenever those impacts are experienced.

Procedures for dealing with aggregation over time are well known and involve the practice of discounting. The underlying principle behind discounting is that (for various reasons) when considering a certain-sized benefit, people attach more value to enjoying that benefit in the present than they do to experiencing it at some point in the future. Indeed, the further ahead in time that benefit is to be experienced the lower the value that people attribute to it. Accordingly, discounting progresses by applying weights to future benefits. These discount weights start at a value of 1 for benefits experienced now and decline progressively over each successive time period, tending to a value of zero in the distant future. Once values experienced at different periods of time have been discounted they can be added together to calculate what is termed the present value of the intervention.

Exactly how the discount weights should be calculated is a matter of ongoing debate. Most often a system of exponential discounting is adopted. Exponential discounting works a little like compounding interest, but in reverse. A discount rate (akin to an interest rate) is selected and the weight is reduced by that percentage amount each year. So with a 10% discount rate, the discount weight in year 0 is 1, that in year 1 is 0.91, that in year 2 is 0.83, and so on.

More recently, support has grown for the use of a declining discount rate. With declining discount rates, a relatively high discount rate is used for years in the immediate future, but for the more distant future progressively lower discount rates are applied. Declining discount rates have the effect of increasing the present value of benefits to be enjoyed in the more distant future. The justifications for this procedure are somewhat technical but at their heart rest on our increasing uncertainty over outcomes in the distant future.

The UK Government publishes guidelines in the Green Book as to the values that should be used in the appraisal of public projects (HM Treasury, 2003).

As well as aggregating over time, values have to be aggregated over people. Clearly a first major issue here is identifying which particular individuals stand to experience a change in welfare as a result of the change in supply of the FEGS brought about by the intervention. In practice the constituency of individuals being considered is often restricted to those that reside within the confines of some political boundary. Indeed, such constraints are common, particularly if that group are also those that are being asked to contribute to the investment delivering the intervention. Of course, that does not mean that the intervention's impacts will only be felt by those in the political constituency. Indeed, an unadulterated application of economic appraisal would wish to identify the welfare impacts on all individuals irrespective of where (or, for that matter, when) they happen to live. That group are sometimes termed the 'economic constituency'.

Increasingly, aggregation over people is being aided by the development of detailed spatial datasets that can be manipulated within a GIS. Data collected from the census provide a reasonably accurate picture of where people live and how their socio-economic characteristics differ across neighbourhoods. Within a GIS, transfer functions can be used to aggregate values across individuals adjusting each individual value for distance decay and differences in socio-economic characteristics.

Uncertainty and irreversibility

Uncertainty is an omnipresent feature of interventions that impact on the environment. That uncertainty may arise because the project's outcomes depend on some fundamentally stochastic process. For example, the project could be investing in new woodlands that reduce downstream flood risks the benefits of which depend on whether or not we experience flood conditions in the future. Alternatively, that uncertainty may arise through a lack of information regarding the intervention's outcomes. For example, the project might be an agri-environment scheme to grow trees as riverine buffer strips so as to reduce pollution in watercourses. The current state of the science, however, cannot tell us for certain how much water quality will be improved by such an intervention. Yet another source of uncertainty arises from our attempts to value the FEGS delivered by an intervention. Since our estimates of those economic values are only estimates usually based on a sample, uncertainty exists in the values that will be enjoyed as a result of an intervention.

There is a substantial and somewhat complicated literature regarding uncertainty and the economic appraisal of interventions. When it comes down to it, however, there are really only two important things that we need to understand in order to handle uncertainty:

- First, people tend to be risk averse such that they regard interventions whose outcomes are not known for certain somewhat less favourably; as a result we need to adjust down individuals' economic values for projects offering the risky prospect of benefits and adjust up individuals' economic values for projects holding out the prospect of possible losses.
- Second, when the outcome of an intervention is uncertain and that intervention results in changes that are difficult or impossible to reverse, then there are benefits associated with delaying the decision to commit to the intervention. Those benefits will only be realised if in the interim we can resolve the uncertainty and find out more about the benefits that the intervention is likely to deliver. For example, if we were uncertain about the environmental consequences of replacing an ancient woodland with a new out-of-town shopping mall, then there would be benefits to delaying the decision to build the mall; but only if new research could provide more definitive information as to the economic value we would lose by clearing the woodland.

Economic values under uncertainty

Before we discuss how we should measure economic values in situations of uncertainty, we should first clear up some terminology. In particular, the sort of uncertainty we are concerned with is one in which we do not know how things are going to turn out for sure, but we can put probabilities on the likelihood of each different potential outcome. Technically speaking, when we know the probability of each different possible future state of the world resulting from an intervention, then the uncertainty is described as a risk. Indeed, some authors reserve the word 'uncertainty' for situations where the probabilities of different possible states of the world are completely unknown. To borrow the terminology of Donald Rumsfeld, we will not concern ourselves here with such 'unknown unknowns'; if we have absolutely no information to guide us then there is not a lot we can do! Moreover, we will continue to use the words uncertainty and risk interchangeably.

For expositional purposes, let us consider a very simple situation in which the uncertainty is reduced to just two possible states of the world. In our example of an intervention intending to plant woodland as a flood mitigation measure, the first state of the world might be one in which flood conditions arise regularly, the second state of the world one in which flood conditions rarely arise. In the wooded buffer strip example, one state of the world might be one in which the buffer strips deliver large improvements in water quality, while the other could be one in which they result in minimal improvements. The analysis can easily be expanded to multiple states of the world, or probability distributions over states of the world, but those generalisations make conveying the intuition more difficult.

The first key issue we have to deal with is how to measure an individual's economic value for an intervention with uncertain (or more correctly, risky) outcomes. An obvious approach would be to first estimate the economic value enjoyed by the household under each possible state of the world as if that were the certain outcome of the intervention. Then a measure of the economic value of the risky intervention could be calculated as the probability weighted sum of those certain values, where the probabilities are the likelihood of each outcome actually being realised. What we would have calculated is termed the expected economic value of the intervention.

If the risks associated with each possible outcome are pretty similar or if the individual whose economic value we are calculating is risk neutral, then expected economic value is likely to be an accurate monetary measure of the welfare change anticipated by that individual as a result of the intervention with uncertain outcomes. When those conditions do not hold, however, an alternative method of calculation of economic value may be called for. That alternative method is called the option price approach.

An option price is the economic value that an individual would express if they were asked to quote their maximum WTP for a risky intervention before knowing the specific outcome. For a risk-neutral individual, this is the same as the expected economic value. For a risk-averse individual, option price will likely differ from expected economic value. In general, since such individuals do not like the prospect of an uncertain future, the option price associated with the risky intervention will be smaller than the expected economic value. The key thing to note here is that option price is the correct measure of the economic value of the risky intervention since it provides an exact monetary measure of the welfare change that an individual experiences by being committed to an intervention that presents them with an uncertain future.

It is not always practical to derive direct estimates of option prices. Given an estimate of levels of risk aversion, however, it is possible to make certain assumptions that allow option prices to be approximated through an adjustment to expected economic values.

To avoid confusion, we should also mention a related measure that is called option value (note option value as opposed to option price). In the environmental economics literature, option value has been defined as the difference between option price and expected economic value. While the details are rather technical, it is now generally accepted that it is difficult to attach a meaningful interpretation to the option value measure and that calculating option values offers nothing further with regards to guiding decisions concerning risky interventions.

Intervention appraisal under uncertainty

Judging the merits of an intervention that offers uncertain outcomes proceeds through the same methods of aggregating across individuals and across time as described previously. The only thing that differs for risky interventions is that the individual economic values that we are aggregating should be option prices.

By extension, one might imagine that discovering that a risky intervention delivers a positive net present value should be evidence enough to justify its implementation. In many cases that might well be true, though things are a little different if the intervention involves changes that make it difficult to return to the former state. We shall describe such interventions as being irreversible, though we are really describing a continuum of situations where going back to how things were is increasingly costly and true irreversibility is just the extreme of that continuum.

When risky interventions result in irreversible changes then an obvious question to ask is whether there is any benefit in delaying a decision in order to resolve the uncertainty. For example, if the economic value of an ancient woodland were not known with certainty, then it might be worth delaying its destruction in order to understand better the benefits provided by the woodland. If those benefits turn out to be substantial, then delaying the decision would definitely have been a good idea. On the other hand, if those benefits turn out to be minimal then we would have incurred a cost related to delaying the development project. It turns out that those costs of delay can be compared to the potential value of avoiding a bad decision in order to work out exactly how much benefit is gained from gathering the information that resolves the uncertainty. This measure is known as the value of information or quasi-option value (or in financial economics, confusingly, real option value).

More formally the value of information is calculated as the difference between two values: (i) the expected net present value of a risky intervention if it is delayed so that uncertainties can be resolved and a better decision made as to whether to proceed and (ii) the expected net present value of that risky project if it is implemented without delay. One can think about the value of information as being the value associated with reducing the potential for regret. And, while we have framed our discussion around the extreme case of gathering information that eliminates all uncertainty, there is value associated with any information which improves our ability to make decisions.

The concept of the value of information is actually fundamental in guiding decisions that involve interventions that are difficult to reverse and result in uncertain outcomes. Discovering whether information has a positive value indicates whether an intervention should proceed on the basis of current evidence or whether it would be worthwhile delaying so as to obtain improved information. Of course, gathering information is not costless. Accordingly the ultimate test of whether delay is worthwhile is whether the value of information exceeds the costs of obtaining that information.

Woodlands and trees have a wide-ranging role in the economy but this is often under-valued in conventional economic indicators. For example, woodlands deliver social and environmental benefits – such as outdoor access, biodiversity and carbon sequestration – which are largely unpriced in economic transactions but which have important impacts on the economy and on society's welfare. This review provides an overview of existing knowledge and evidence on the social and environmental outputs of forestry in Britain and identifies priorities for future research. It uses the concept of the 'natural factory' to explain how natural assets such as woodlands contribute to different economic production processes. It evaluates underpinning scientific research, economic valuation evidence, and provides a separate assessment for urban trees and woodlands. It also examines evidence needs relating to key developments in economic thinking and practice including natural capital accounting and a new generation of integrated decision support tools. Despite a substantial extant body of evidence, further research is needed to fill significant gaps in knowledge in order for the full economic contribution of woodlands to be understood.

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