Natural Capital Metrics

Phase 1 Final Report: Central components

CEH Project NEC06063

Lead authors:
Harrison, Paula; Sier, Andrew; Acreman, Mike; Bealey, Bill; Fry, Matthew; Jones, Laurence; Maskell, Lindsay; May, Linda; Norton, Lisa; Read, Daniel; Reis, Stefan; Trembath, Philip; Watkins, John

Contributing authors:
August, Thomas; Bachiller-Jareno, Nuria; Beck, Rachel; Bogdanova, Maria; Brown, Mike; Bullock, James; Blyth, Eleanor; Carnell, Ed; Carss, Dave; Carvalho, Laurence; Carvell, Claire; Cosby, Jack; Dunford-Brown, Robert; Goodall, Tim; Gweon, Hyun; Hall, Jane; Harrower, Colin; Henrys, Peter; Isaac, Nick; Kazlauskis, Karolis; Kral, Filip; Laize, Cedric; Marthews, Toby; Masante, Dario; Mills, Gina; Morton, Daniel; Nemitz, Eiko; Old, Gareth; Oliver, Anna; O'Hare, Matthew; Redhead, John; Rennie, Susannah; Rhodes, Glenn; Roberts, Elin; Roy, David; Scholefield, Paul; Smart, Simon; Smith, Katie; Stratford, Charlie; Taylor, Philip; Vieno, Massimo; Wilson, Mike; Winfield, Ian; Woods, Helen; Wright, Dan

May 2017

Project funded by Natural Environment Research Council (National Capability funding)

APPROVED FOR EXTERNAL RELEASE

Natural Capital Metrics project NEC06063

Final report: Central components

Contents

About this report

This is a condensed version of the Natural Capital Metrics (NCMet) project Phase 1 report. It focuses on three key components: i) the conceptual framework, ii) development of six example evidence-chains and their associated data and model inventories, and iii) early development work towards a Natural Capital Portal to provide access to relevant data, models and maps of natural capital.

All outputs are preliminary and are undergoing considerable refinement in the second phase of the project. Phase 2 outputs will be available in 2018.

1 Background and objectives

Humans are dependent on goods and services provided by the natural environment. These are delivered by assets such as soils, trees, water, air and insect pollinators. The term natural capital is used to recognise the importance of nature's assets and the benefits that flow from them in the form of ecosystem services.

CEH has unrivalled expertise and experience in the science of the natural environment that underpins natural capital. We collect data through surveys and monitoring (e.g. Countryside Survey (CS), Glastir Monitoring and Evaluation project (GMEP), Environmental Change Network (ECN)), and add value by incorporating data from external sources, such as through the Biological Records Centre (BRC) or National River Flow Archive (NRFA). These environmental datasets can be used to define measures of natural capital that relate to ecosystem services and human benefits. However, this often requires datasets to be translated or combined in complex ways because of multifaceted interactions and the multiple benefits that arise. For example, the existence of woodland, its location in a catchment, the interaction of the trees with soil all combine to determine carbon storage, flood management, recreation and biodiversity. CEH has developed in-house models, such as Ecomaps, and uses external models, such as InVEST, LUCI and ARIES, to explore such interactions and understand how decisions on management or restoration of environmental assets will deliver different levels of natural capital and ecosystem services.

CEH's Natural Capital Metrics (NCMet) project aimed to integrate CEH and external data, models and scientific knowledge to assess natural capital assets, ecosystem services and human well-being. We envisage that this science will underpin policy implementation, such as natural flood management, ecosystem accounts and the Defra 25 year plan for natural capital restoration.

The objectives of the NCMet project were to:

1. Define a conceptual framework for linking natural capital assets to human well-being, identifying and providing an evidence base for each step along the chain.
2. Produce inventories of available datasets that contribute to knowledge of natural capital assets.
3. Identify and make available best knowledge of the processes and functions that define the interactions among natural capital assets, and how such interactions underpin the delivery of ecosystem services (e.g. through reviews).
4. Catalogue and apply models that use this best available knowledge and recent data processing capabilities (such as cloud computing) to combine natural capital datasets and produce outputs that are, or can be transformed (e.g. by economists) into, measures of ecosystem services and human well-being.
5. Develop knowledge exchange and communication tools, such as portals on the CEH website, to provide access to datasets and project outputs, and to enable exploration of the chain of evidence linking natural capital to ecosystem services and human well-being.

2 Conceptual framework

The development of the NCMet conceptual framework was an iterative process based on reviews of other conceptual frameworks, identification of the key questions that the conceptual framework (and hence the NCMet project) aimed to address, and iterative refinement based on feedback from project participants and external stakeholders.

Several existing conceptual frameworks were reviewed, including:

- Cascade model (Potschin and Haines-Young, 2011) and various extensions or refinements of it by van Oudenhoven et al (2012), Boerema et al. (2016) and Saarikoski et al. (2015).
- Framework for Ecosystem Service Provision (FESP) based on the Drivers-Pressures-State-Impact-Response (DPSIR) framework by Rounsevell et al. (2010).
- Framework for Final Ecosystem Goods and Services (FEGS) developed by the US-EPA (Landers and Nahlik, 2013).
- Components of an ecosystem service supply chain by Tallis et al. (2012).
- Framework for combining stocks and flows of natural and human-derived capital in ecosystem services by Jones et al. (2016).
- Conceptual framework of the Natural Capital Committee (NCC).
- Various frameworks of the Office for National Statistics (ONS) related to natural capital accounting.
- Conceptual framework of the Welsh Government highlighting linkages between seven well-being goals, ecosystem services and natural resources.
- Conceptual framework of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES).

Several key questions that the conceptual framework of the NCMet project aimed to address were identified:

- Which natural capital assets underpin an ecosystem service or human benefit?
- What human benefits does a natural capital asset or combination of assets produce?
- How do different natural capital assets combine to produce benefits?
- What aspects of natural capital assets are important for delivering ecosystem service benefits (stock, quality, spatial configuration, biotic/abiotic, etc.)?
- What human benefits are produced by the natural capital assets associated with the UK broad habitats?
- What management responses can improve the delivery of human benefits from ecosystem services?
- How do natural capital assets and ecosystem services respond to certain drivers of change (or combinations of drivers)?
- What responses improve the resilience of natural capital assets (and the benefits they deliver) to drivers of change?

During the first year of the project, it was recognised that we would focus on the first three questions above to establish the evidence associated with current interactions and linkages between natural capital assets, ecosystem services and human well-being. However, the conceptual framework was designed to cover all identified questions flexibly, including those related to drivers, impacts and responses.

The existing conceptual frameworks were matched with our key questions to identify those elements that might be worth taking forward into the NCMet conceptual framework. This revealed that many of the existing frameworks include characteristics of the biophysical or ecological system and of the human or socio-economic system, with ecosystem services joining the two. Properties included in the biophysical system varied, but encompassed ecosystem properties, natural resources or natural capital assets in general or specific ecosystem structures, processes and functions. Some frameworks differentiated intermediate and final ecosystem services (FEGS and Saarikoski et al. (2015)), others differentiated between ecosystem stocks (extent and condition) and ecosystem service flows (ONS), whilst others linked natural capital assets to major land use types (NCC, ONS). Properties included in the human system also varied, but encompassed beneficiaries (and their preferences or demand for services), benefit, value and aspects of human well-being. A few also highlighted other types of capital that may be required to realise an ecosystem service flow (Jones et al., 2016; NCC and FEGS in part). In terms of ecosystem services, most frameworks include them in general (i.e. as a single entity), with a few breaking them down into provisioning, regulating, cultural and supporting services (e.g. Welsh Government). Finally, many of the frameworks did not include drivers, pressures and responses, the FESP being the main exception as this is based on a DPSIR approach.

These considerations were taken into account in designing a draft NCMet conceptual framework. The framework was then iterated around project partners for comment and to selected external stakeholders at various events, such as the JNCC Natural Capital Metrics meeting and a Defra meeting. Figure 1 shows the final version of the NCMet conceptual framework. The framework is broadly structured around the DPSIR approach which emphasises the role of humans-in-nature (Berkes and Folke 1998), similar to the concept of socio-ecological systems (Gallopin, 1991). It builds on the FESP (Rounsevell et al. 2010) in terms of drivers, pressures and responses, but integrates further detail into what would be the state-impact box (blue dotted line in Figure 1: NC Metrics project Conceptual Framework for a single socio-ecological system) on the different interacting components of the ecological and socio-economic systems drawing on the experience of other frameworks.

External drivers represent the underlying causes of environmental change that are beyond the boundaries of the socio-ecological system under consideration, e.g. climate and socio-economic change. External drivers are embedded within the broader Earth System. External drivers lead to changes in internal pressures that are a component part of the socio-ecological system, e.g. temperature, precipitation, land cover, regional population. The internal pressures change the state of the socio-ecological system and directly influence natural capital assets and ecosystem services. Natural capital assets are characterised by ecosystem properties, such as stock, condition and structure, and ecosystem functions that represent flows or processes. The natural capital assets combine to produce different ecosystem services (and potentially also disservices, such as invasive species). The ecosystem services themselves interact resulting in trade-offs and synergies between different types of services (provisioning, regulating and cultural; supporting services are assumed to be part of the natural capital assets). The ecosystem services are provided to beneficiaries, which also influence service supply through their preferences, including different characteristics of demand (such as location, social or economic attributes of the population), the benefits supplied and how they are valued. Other capitals may be required to realise an ecosystem service flow; some of these are embedded in beneficiaries such as human, social and cultural capital, whilst others are external such as produced or financial capital.

Impacts on the socio-ecological system from pressures may trigger responses that can be based on solutions to negative impacts or the exploitation of opportunities with positive impacts. Policy, planning and management strategies can be used to maintain or enhance natural capital assets (influencing the supply of ecosystem services) or to modify other capital inputs or beneficiary demand for ecosystem services. Responses also interact with internal pressures. A response may aim to reduce the magnitude of a pressure, for example, pollution control strategies. However, at the same time, pressures act on the responses themselves and need to be resilient to multiple interacting pressures. Theoretically it is possible for responses to act on external drivers, for example climate change mitigation, but in practice the magnitude of these effects is likely to be trivial at the UK national scale.

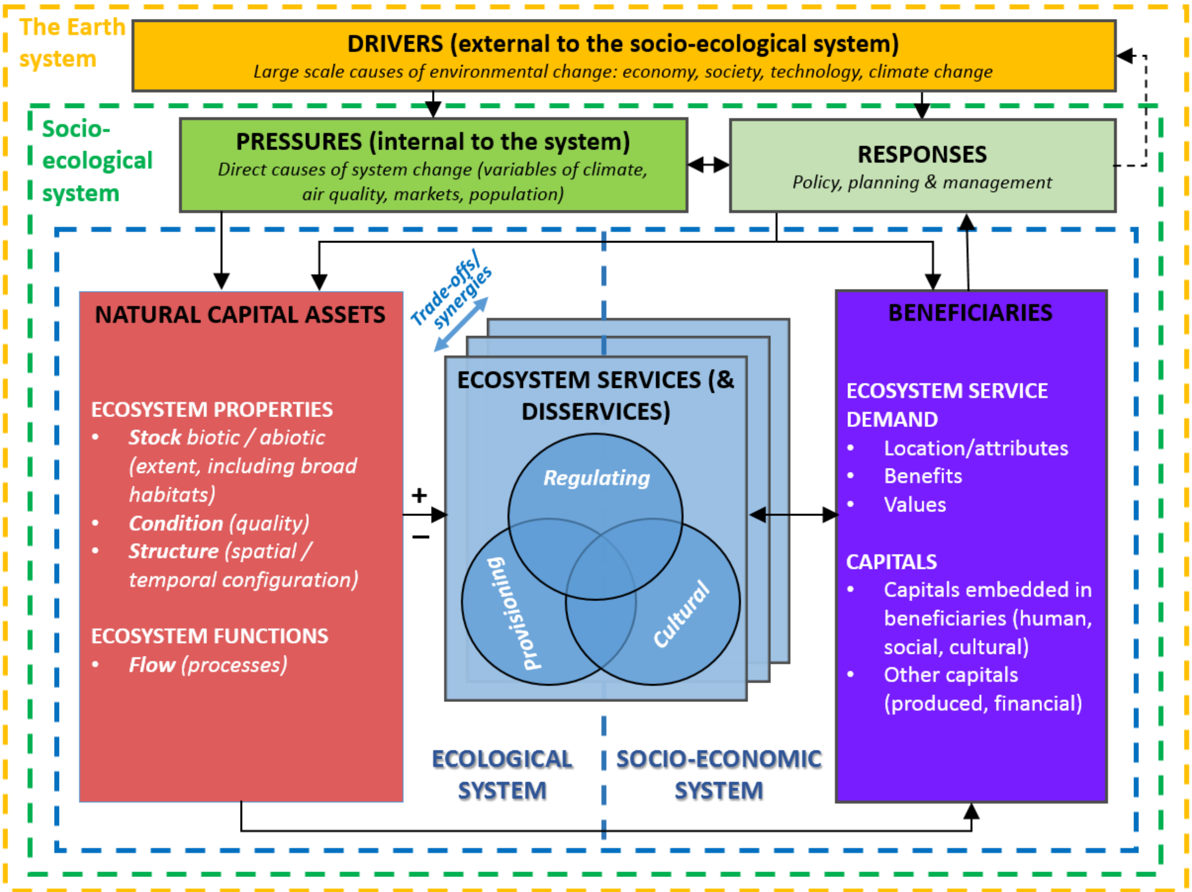


Figure 1: NC Metrics project Conceptual Framework for a single socio-ecological system

Figure 1 shows a conceptual framework for a simple representation of a single socio-ecological system. In practice, however, conflicts and trade-offs exist between multiple socio-ecological systems each with multiple drivers, pressures, ecosystem services and beneficiaries (as illustrated in Figure 2).

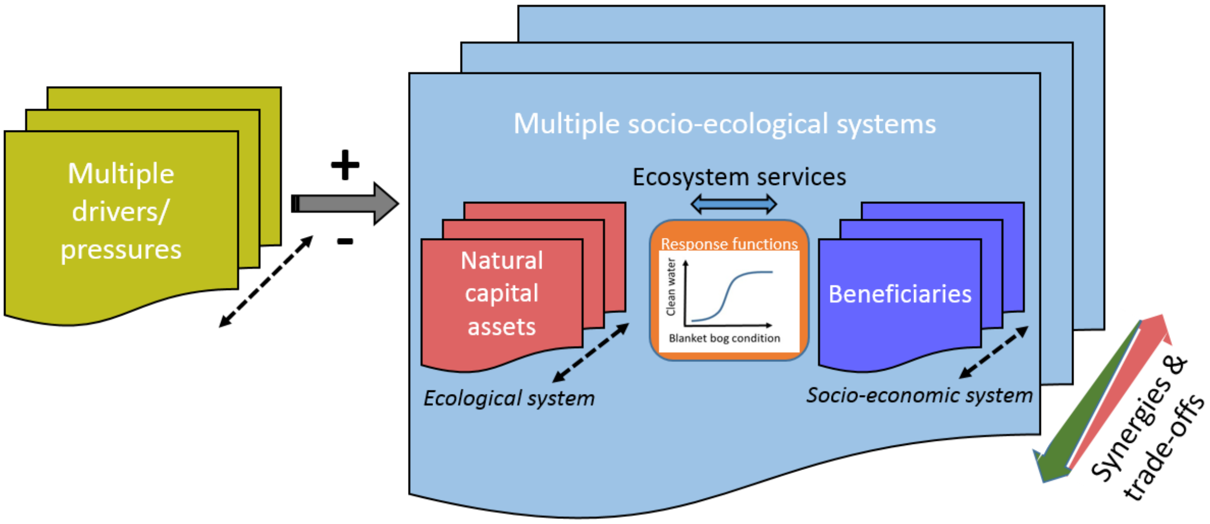


Figure 2: NC Metrics project Conceptual Framework for multiple socio-ecological systems

3 Evidence chains

Evidence chains provide a description of the linkages and interactions between natural capital assets and ecosystem services and human benefits. Research in the first year focused on developing evidence chains and their associated datasets (Section 4) and models (Section 6) for selected case studies from land, water and air systems:

- **Pollination**
- **Lake water quality regulation**
- **Flood mitigation through tree planting**
- **Flood and drought mitigation through riverine vegetation**
- **Conflicts between seabird conservation and the development of renewable energy sources**
- **Benefits of trees on air quality and human health**

These evidence chains are presented in the following pages, along with the evidence that supports each component of the chain, including gaps in evidence and implications for monitoring strategies. All evidence from the literature has been included in the evidence chains where deemed appropriate, but evidence may have different strengths depending on its quantity and quality (see Box 1). Each evidence chain is presented using a consistent graphical format (known as a data graph) that was developed during the scoping of the natural capital portal (see Section 7).

Box 1: Evidence reviews

A review of previous research and the evidence that it has produced is a first step in most projects.

However, reviews are vulnerable to personal bias and, at worst, can involve selection of literature to support a predefined view. There are many ways in which the review process can be made more objective, including pre-specification of protocols that define search terms, sources, exclusion/inclusion criteria and analysis methods.

The systematic review is perhaps the most comprehensive, rigorous and reproducible evidence assessment method that includes, for example, separate teams using the same selection criteria on a common subset of papers to check consistency of application. To avoid the subjectivity of any inference made by authors in summary text, a systematic review often includes extraction of data or results from papers for subsequent meta-analysis. In this way, results of many studies can be combined giving a more reliable and precise estimate of an intervention’s effectiveness than can be provided by one study alone, making conclusions more defensible. Recent developments in the approach have included weighing the evidence according to the study methodology; for example, studies with controls and replicates may be given higher weight that studies without them. Weighting provides a valuable tool for comparing different sources of evidence that may be inconsistent or contradictory. As well as setting out what we know about a particular intervention, systematic reviews can also demonstrate where knowledge is lacking.

Since a full systematic review is very time consuming and expensive, abbreviated versions have been developed, with significant input from CEH including Rapid Evidence Assessment and Quick Scoping Reviews (Collins et al., 2015).

A key aspect of understanding and quantifying links between natural capital assets and benefits to people is defining the underpinning scientific evidence. Evidence reviews provide this information and an audit trail.

3.1 Land case study - Pollination

The pollination service was chosen as a case study because of the readily available national scale data collected on: (a) plants providing pollen through both Countryside Survey (CS) and National Plant Monitoring Scheme (NPMS); and (b) pollinating insects through volunteer recorders as part of the BRC/National Biodiversity Network (NBN) datasets. A diagram was constructed (Figure 3) showing the relationships among the data that were collected and the final service of pollination, including any key drivers affecting those relationships. Inevitably, there are enormous complexities in these relationships (e.g. the importance of nesting sites, the role of predators, etc.) but the aim was to keep the approach relatively simple. Evidence from CS data on species presence is strong due to the design of the survey technique, which provides spatially representative information on GB habitats (species presence and cover but not extent of flowering). However, such data are available only for survey years. In contrast, NBN datasets contain pollinator records collected over a long time period, but these records are not designed to be spatially representative (except in the case of butterfly monitoring data) and include information on presence only (as opposed to numbers of individuals). Relationships between driving variables, i.e. N deposition, Broad Habitat and precipitation, are evidenced by GLM modelling approaches (Ecomaps) which have significant impacts on the presence of nectar producing species. Weaknesses in the evidence chain (because data are lacking) are highlighted below:

- Lack of monitoring data on the timing/presence/extent of flowering of nectar plant species;
- Lack of knowledge regarding which pollinator species pollinate which plants and when, (though we do have some lists for specific pollinators, bees/butterflies in particular);
- Lack of knowledge regarding the importance of pollinators to crop plants – which crops rely on insect pollination, which pollinators do they rely on?

In some of these areas there may be potential for CEH to fill these gaps through modifications in monitoring approaches, the use of other datasets (including trait data held by CEH) or future research. Other areas where current monitoring data may help to provide a better understanding of the national extents of pollinators include CS data on extent and condition of non-crop habitats like hedges (as pollen or nesting site resources), etc. The process raises research questions such as: How effective is pollination? How many pollinators do you need to ensure adequate pollination? What are the relationships between crop pollination and the presence of non-crop plants in the agricultural land matrix? What is the role of disease in regulating pollinator numbers? What are the relationships between wild and introduced pollinators?

The evidence chain also highlights the need for work linking socio-economic data to CEH data to enable translation of our natural capital data into service provision. For pollination, such work would include information about yield from crops and the aesthetic ‘value’ of flowering plants to ‘consumers’, such as those visiting the countryside. It may be possible to evidence some links with existing information, e.g. the influence of biodiversity on appreciation of grassland vegetation (Lindemann-Matthies *et al.* 2010), but quantifying these links is likely to be more difficult.

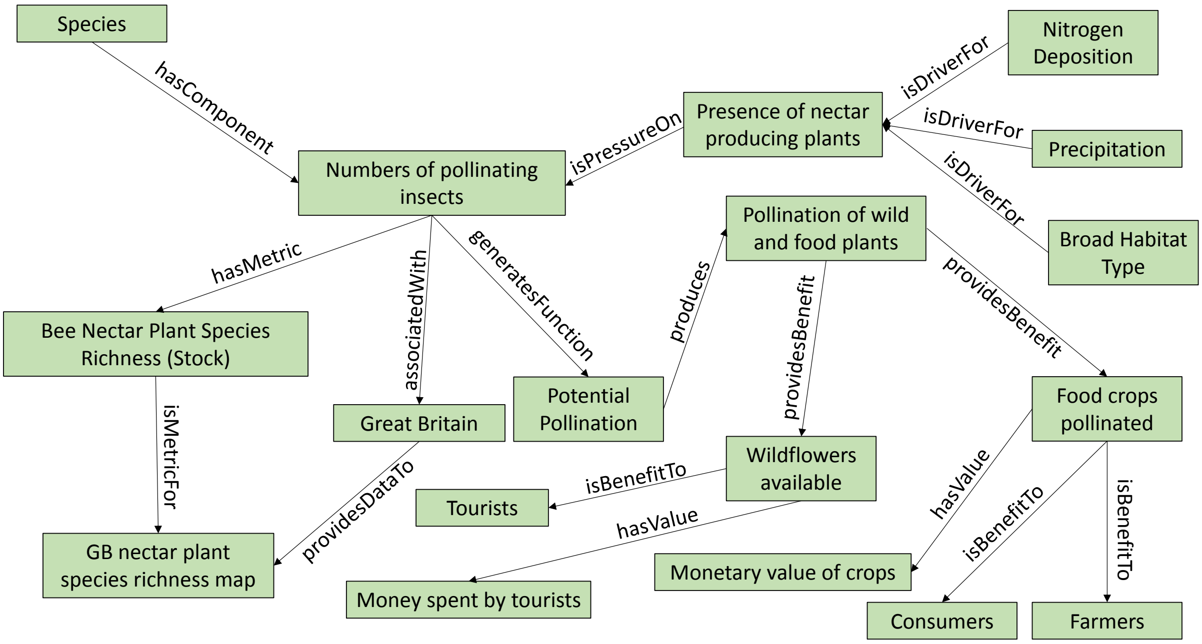


Figure 3**: Data graph illustrating pathways for the service of pollination**

3.2 Water case study - Lake water quality regulation

Water is essential to many aspects of life on earth. Its suitability for uses such as drinking water and recreational use depend on the quality and quantity of the freshwater asset. Figure 4 shows the evidence chain for lake water quality regulation that determines its suitability for drinking water and recreational use. Although, in reality, this process is very complex, there are three important overarching relationships in this evidence chain. These are between:

- land use and nutrient inputs to lakes;
- phosphorus concentrations and cyanobacterial concentrations in lakes; and
- cyanobacterial concentrations and likelihood of failing to comply with World Health Organisation (WHO) safe levels for drinking water and recreational use.

Land use and nutrient inputs to lakes

Many studies have demonstrated a very strong link between land use within the catchment and the level of nutrient input to rivers and, subsequently, lakes. This relationship is affected by changes in land use (potential supply of nutrients) and climate (potential delivery of those nutrients to water). As such, future changes in land use and climate will affect the delivery of potable water supply and recreational facilities by lakes.

Phosphorus concentrations and cyanobacterial concentrations in lakes

The concentration of algae in lakes is driven by a variety of factors including nutrient inputs, flushing rate, water temperature and solar radiation. However, a key factor that affects the likelihood of troublesome, and sometimes toxic, algal blooms developing is phosphorus (P). Higher inputs of P from the catchment result in higher in-lake P concentrations and these increase the likelihood of cyanobacterial blooms developing.

Likelihood of failing to comply with World Health Organisation (WHO) safe levels for drinking water and recreational use

When lakes exceed WHO thresholds for safe levels of cyanobacteria, increased water treatment costs are incurred and/or sites may be closed to the public until the problem has been resolved. Increased water treatment costs and loss of income due to restrictions on recreational use (either of the lake itself or the surrounding area) have economic consequences for local businesses. These have a monetary value that can be measured.

In addition, there are human and animal health implications (illness; death) when cyanobacterial concentrations exceed WHO thresholds. The cost of these incidents can also be measured in terms of incidents reported, and in costs to the NHS and to the owners of pets and livestock.

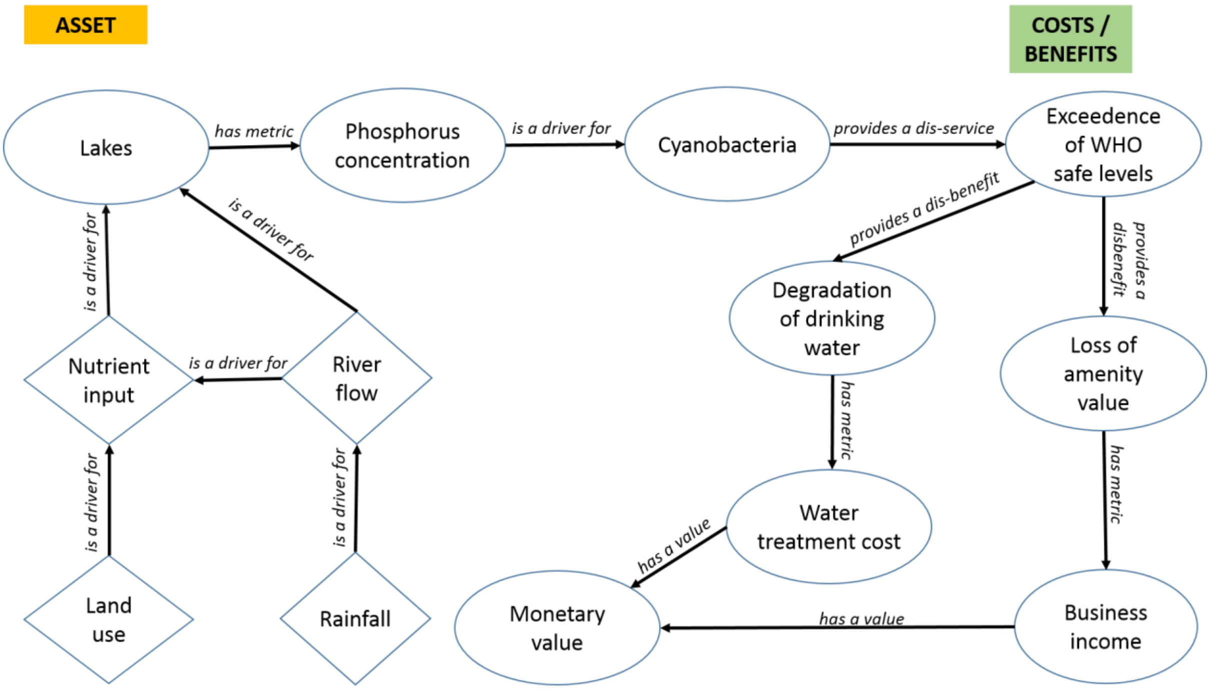


Figure 4: Data graph illustrating pathways for the service of lake water quality regulation

The sources of evidence linking a variety of drivers (e.g. land use/nutrient delivery; rainfall/river flow) to lake water quality regulation are shown in Figure 5. These include nutrient delivery models and lake response models.

Strength of evidence and gaps in knowledge

Although there is strong evidence that elevated nutrient inputs to lakes increase in-lake P concentrations and, consequently, the likelihood of troublesome cyanobacterial blooms occurring, these conclusions are mostly based on annual (summary) data rather than more detailed data that are collected more frequently (i.e. daily/weekly to seasonally). So, our knowledge of how future changes in climate and/or land use will affect these relationships is limited. This is an important issue, because parameters such as biological response and changes in amenity value are strongly affected by seasonality. For example, the impact of water quality problems on the economic value of benefits to people will vary seasonally, because recreational usage tends to be lower in winter than in summer. We need well monitored lakes and catchments with good access to related socio-economic data (visitor numbers, income to local businesses, etc.) to address this issue and develop suitable metrics for measuring changes in the value of these assets and the benefits that they provide.

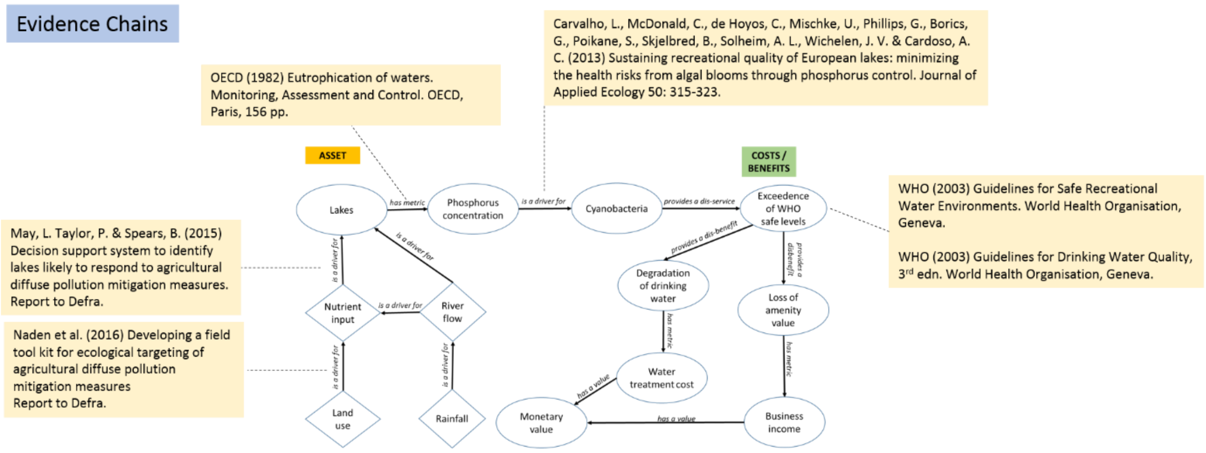


Figure 5: Evidence sources linked to the lake water quality regulation data graph

Although we understand some of the relationships between water quality and biological responses in relation to single stressors, and in relation to water quality degradation, the impacts of multiple stressors on lakes and catchments are poorly understood – especially in relation to the restoration of freshwater assets and/or the remediation of environmental impacts. When those responses are affected by large scale changes in multiple pressures, such as land use and climate change, cause-effect relationships are difficult to disentangle experimentally. Only long-term, real world datasets can provide the evidence that we need to understand how multiple pressures interact and how their combined effects either directly or indirectly affect the quality of our freshwater assets and the benefits that they deliver to people at the landscape scale and beyond.

Finally, the links between chemical and ecological water quality (asset) and service provision (benefit) are still very poorly understood for most lakes. As a first step, quantification of these relationships, and of the ecosystem processes on which they depend, should be based on detailed studies at sites that can provide sufficiently frequent (at least fortnightly) monitoring data on water quality and benefits. Later, the potential for scaling up to a larger number of lakes should be explored. Potential methods for scaling up might include the use of ratios of variables commonly monitored for WFD purposes, e.g. P:chlorophyll *a* concentrations, as proxies for ecosystem system function and service delivery (e.g. water purification, fishing quality, etc.).

3.3 Water case study – Flood mitigation through tree planting

Following widespread flooding across Cumbria and other parts of northern Britain in December 2015, there has been renewed interest in the potential role of natural solutions, particularly afforestation, in mitigating flood severity. The complexity inherent in the influence of trees on river flooding makes the formation of a clear opinion difficult and, whilst there is pressure to reduce the flood risk, the lack of a robust review of evidence is causing confusion and inhibiting adoption of effective policy. CEH have, therefore, carried out a review of this evidence using systematic review principles in order to bring clarity to this issue. The review focuses on the impact of trees on river flooding, looking specifically at river floods resulting from above average rainfall. The evidence from the review was used to construct an evidence chain for flood mitigation by tree planting (Figures 6 and 7).

The presence of trees in a catchment have the potential to influence river flows by intercepting rainfall, increasing soil water storage as a result of evapotranspiration leading to soil moisture deficit, and diverting surface water flows. These factors can, individually or collectively, reduce downstream flood peaks. However, the extent to which trees influence flood peaks is largely dependent on other factors such as the area of cover, density and position of trees in the catchment, soil moisture conditions when the flood event occurs, and the magnitude and intensity of the rainfall event leading to flooding. For these reasons, developing a simple relationship between tree cover and flood peak reduction is not possible.

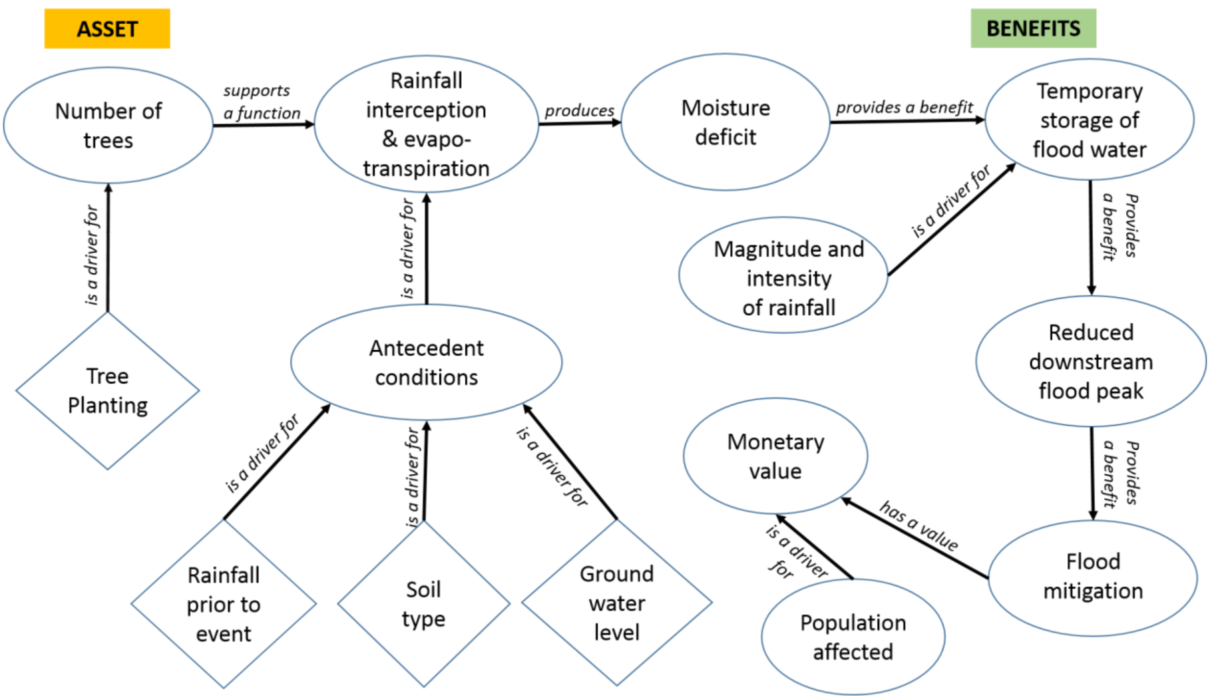


Figure 6: Data graph illustrating pathways for the service of flood mitigation through tree planting

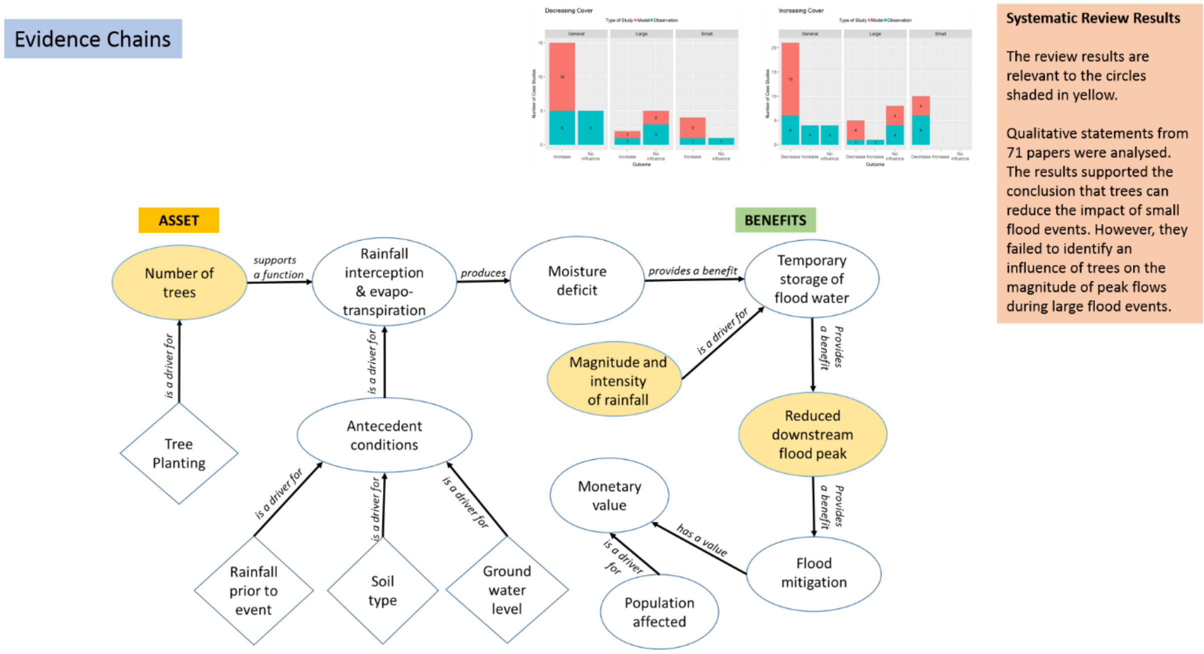


Figure 7: Evidence sources linked to the flood mitigation data graph. Note that the evidence is sourced from a systematic review undertaken within the NCMet project

At all stages of the systematic review the project team worked closely with the review advisory group, which included representatives from research, application and policy, to ensure that the steps carried out were consistent with the desired outputs. Through discussion with the group, the review question was agreed as ‘Do trees in UK-relevant river catchments influence fluvial flood characteristics?’ and a list of key words that commonly describe the aspects of the review question was compiled. This list was combined to form a text string with which Web of Knowledge was searched:

```
(Landscape OR river OR catchment OR basin OR *stream* OR channel OR
watershed) AND (Planting OR *forest* OR tree* OR wood* OR logging OR
"land use" OR regenerat* OR fell* OR timber OR plantation OR clear-
cut* OR scrub OR coppic* OR “land cover”) AND (*flow* OR level OR
flood OR discharge OR runoff OR yield OR volume OR duration OR
hydrolog* OR inundat*)
```

The studies considered were constrained by geographic location based on the Köppen climate classification (Figure 8).

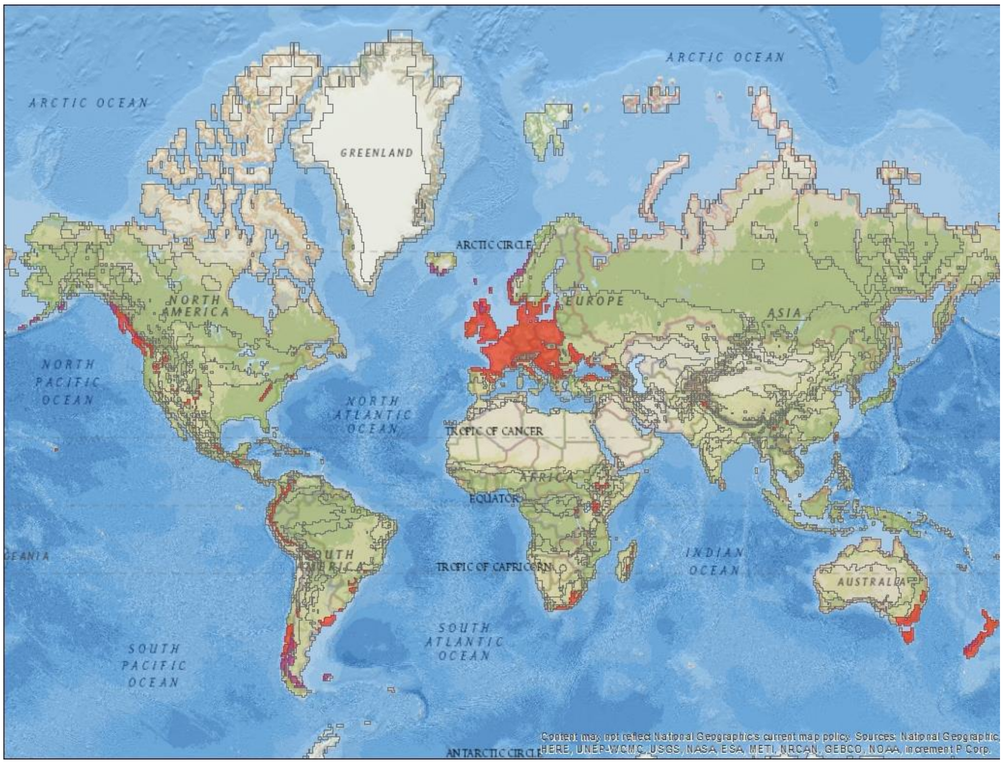


Figure 8: Regions of the world with the same Köppen classification as the UK (areas shaded red)

The initial Web of Knowledge search, using the search string and geographic constraint described above, returned 19,337 potentially relevant references. These were screened using algorithms developed in Microsoft Excel and 5,198 references were identified for manual checking of titles and abstracts. In total, 462 papers (plus a further 37 identified during previous work) were identified as being eligible for full text screening and, from these, 71 papers were accepted for qualitative data extraction.

From each of these 71 papers, qualitative statements relating to the influence of trees on flood peaks were captured along with information on the type of experimental design, whether the study looked at increasing or decreasing tree cover, whether the study findings were based on observed or modelled data, and (where possible) the relative size of the flood event (small or large). Results were initially split into two groups for analysis, i.e. increasing cover or decreasing cover. In both cases, there was broad support for the conclusion that the presence of trees reduces flood peak.

We then looked at the results in more detail, first making a distinction between results based on observed and modelled data and then distinguishing between small and large flood events. This subsequent analysis identified some notable patterns within the results (Figure 9). Firstly, modelled results are largely responsible for the conclusion that trees reduce flood peak; if observed studies only are considered, the evidence is much weaker. Secondly, the majority of observed studies report that trees have no influence on the peak flows of large flood events.

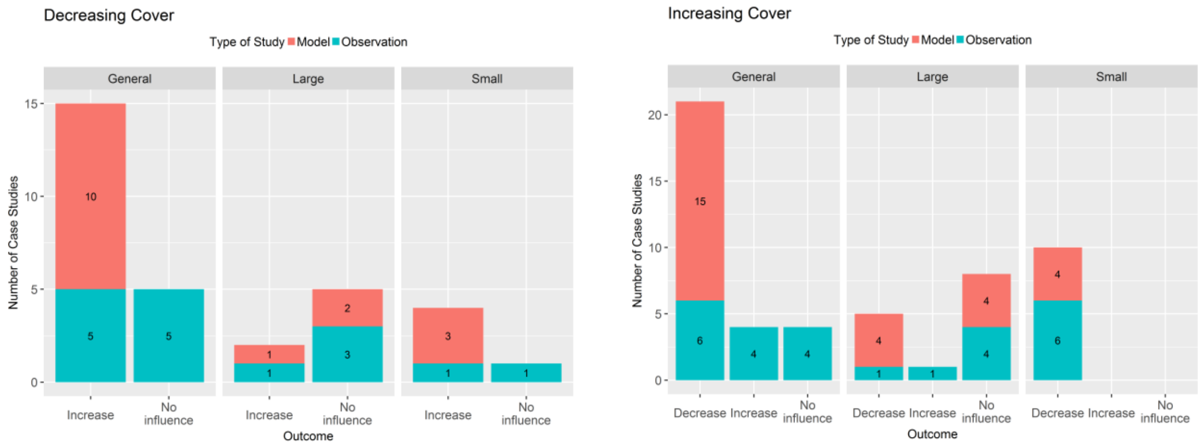


Figure 9: Results of qualitative evidence review of the influence of trees on flood peak

In summary, the review achieved the following objectives:

- A broad and detailed search, using search terms agreed by the advisory group, of all potentially relevant peer-reviewed literature available through the online reference database, Web of Knowledge.
- Assessment of all literature identified as having potential relevance and systematic screening according to criteria agreed by the project group; all relevant literature has been stored in a database.
- Extraction of contextual information and, where presented, qualitative statements regarding the influence of trees on flood peaks from each of the references meeting the selection criteria.
- Analysis of the qualitative statements and summary of the overall review findings.

3.4 Water case study – Flood and drought mitigation through riverine vegetation

Riverine vegetation and its management is something of a Cinderella topic in environmental management. In-stream vegetation has a crucial ecosystem engineering role, is vitally important for water quality and flood management, and costs an enormous amount of money to manage. Environment Agencies, Drainage Boards and Councils are in a constant battle to cut back and remove natural growth and prevent succession processes. However, compared to other riverine management topics, it has received relatively little research attention. Despite this limited effort, over the past 40 years, CEH and researchers globally have managed to disentangle key aspects of the role of vegetation in river ecosystems.

The blocking of channels is not necessarily a bad thing, nevertheless the benefits of channel blocking is an area of research that has received only partial attention. We know that aquatic plants are keystone species in rivers and provide important environmental services. For example, they increase water depth during the summer months, which provides wetted habitat for invertebrate and fish species (Gurnell & Midgely 1994). They also boost habitat complexity by providing shelter and varied flow conditions, which support large numbers of invertebrates and juvenile salmonid fish. In effect, the presence of aquatic plants means that more environmental benefit is derived from each drop of water that passes through the system. This is especially important in systems that are subject to abstraction. However, the benefit of aquatic plants to the floodplain has received little attention, particularly the benefit of elevating the water table in surrounding farm land which reduces the need for irrigation. While this has not been studied in the UK, there is some work from the Netherlands that can be used to infer the relationship from arterial drainage, where river beds are lowered to drain farmland.

The fundamental dynamic is simple, a channel's resistance to water flow is varied by plants growing within and along its margins (Gurnell & Midgley 1994). This forms the basis of the asset to benefit relationship shown in Figure 10 and the evidence that underpins it as shown in Figure 11. The effect of the vegetation is determined by its amount and type (O'Hare et al 2010). Different vegetation types dominate different river styles, so the plant-flow interactions are style specific (O'Hare et al 2011). Hydrologists incorporate vegetation into their estimates of a channel's capacity to carry water by using reference values for different vegetation states; the industrial standard are Manning's n values.

Environmental management underpinned by legislation now demands a higher tolerance of aquatic plant growth in channels than has traditionally been the case. The traditional estimates of Manning's n are inaccurate and not specific enough to be useful for current applications (McGahey et al 2008). CEH has helped to improve this situation but there is a need for further research to address knowledge gaps in this area. In particular, there is a need to collect data on vegetation effects on flood flows, a topic that has received next to no research attention despite its critical importance.

Variations in flows and aquatic plant abundances are rarely quantified, making it challenging to estimate the potential conveyance of a channel with any known degree of certainty. Traditionally, estimates of flow resistance in vegetated channels have relied on values in look - up tables, e.g. Cowan's method. These tables contain Manning's n roughness values across broad vegetation categories, e.g. no vegetation, dense weeds etc. Although single categories have been used to represent different types of vegetation, plants species can interact with flow in many different ways (McGahey et al 2008, O'Hare 2015); this needs to be incorporated into the future development of conveyance models.

Finally, there is strong evidence that eutrophication can exacerbate flood risk by increasing plant biomass in channels (O'Hare et al 2010) and that routine weed cutting and channel dredging can significantly alter plant community structure and abundance (Wade 1990). For example, it has been known since the 1970s that current weed cutting practices can actually stimulate plants and lead to denser growth, but this practice is still current. Further research is required to determine the management practices that are best to maintain aquatic plant communities within rivers and the benefits that they provide.

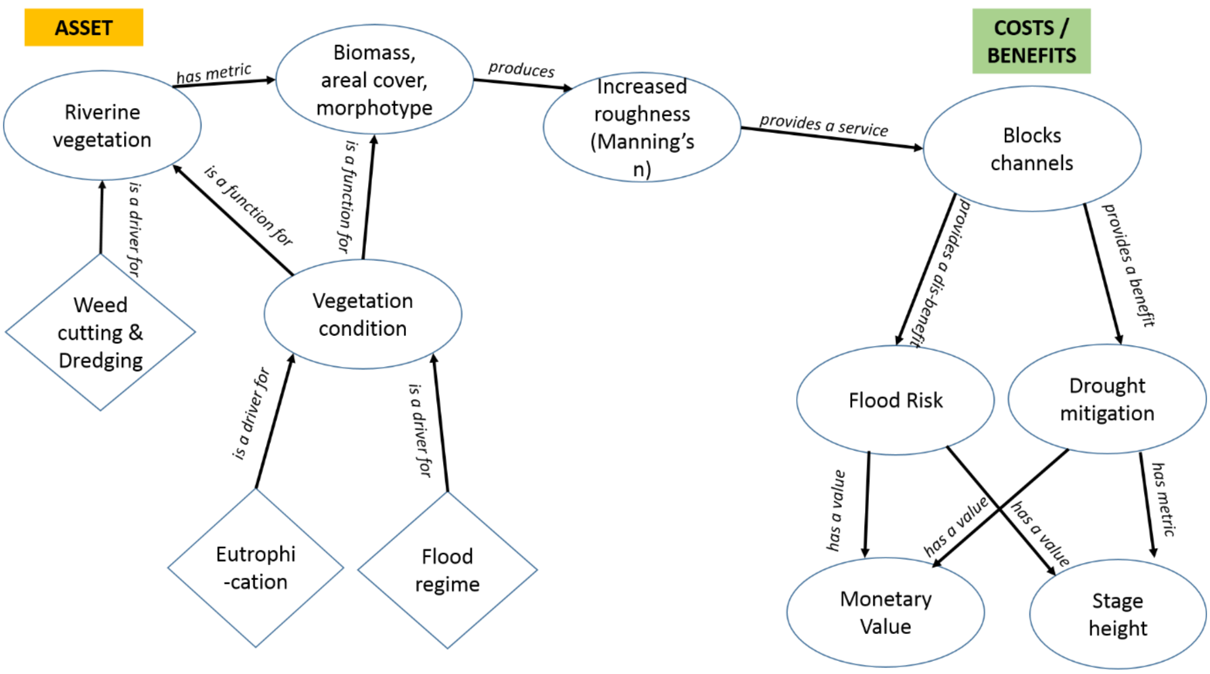


Figure 10: Data graph illustrating pathways for the service of flood risk and drought mitigation through riverine vegetation

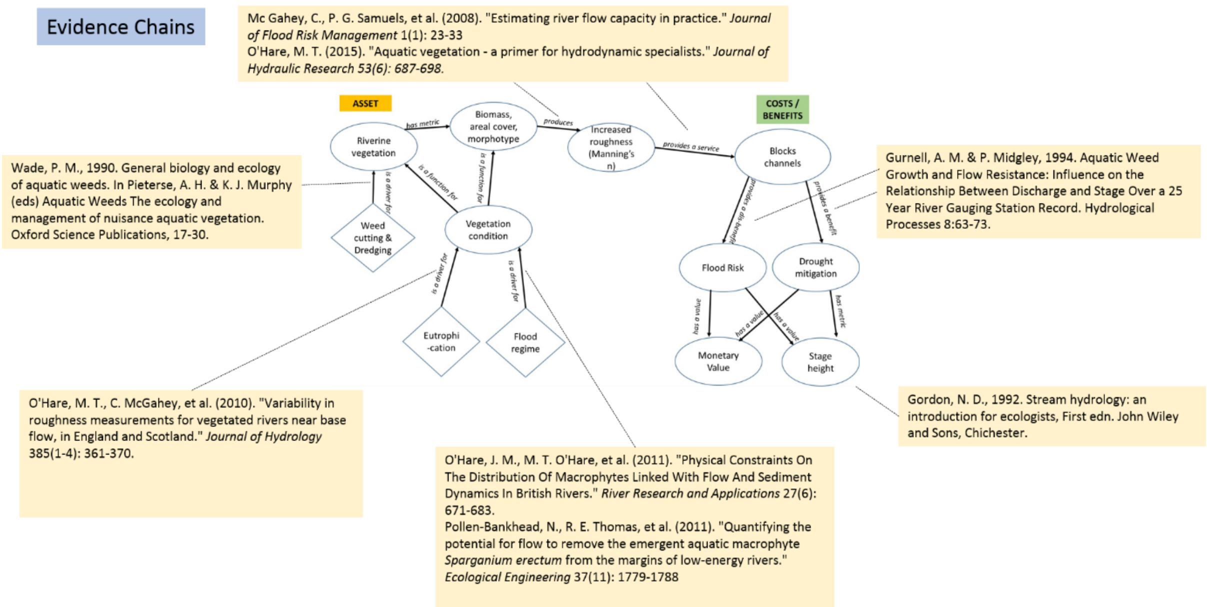


Figure 11: Evidence sources linked to the flood risk and drought mitigation data graph

3.5 Water case study – Conflicts between seabird conservation and the development of renewable energy sources

Coastal marine ecosystems sustain rich biodiversity and at the same time are subjected to increasing pressure from human activities such as fisheries, oil and gas extraction, shipping and renewable energy generation (Douvere & Ehler 2009). As apex predators, seabirds are a key component of the marine food chain and seabird population dynamics are an important indicator of the health of marine ecosystems and environmental change (Furness & Camphuysen 1997). Furthermore, the UK holds internationally important breeding populations of a number of seabird species and has a legal obligation to protect them under the European Birds Directive (EU 2009).

The importance of renewable energy generation is growing globally in conjunction with mitigating the effects of anthropogenically induced climate change. The UK is legally committed to meeting 15% of its energy demands from renewable sources by 2020, contributing to energy security and decarbonisation objectives. In 2012, proposed UK renewable deployments totalled £12.7 billion in investment with the potential to create 22,800 jobs. Marine renewables (offshore wind and wave/tidal) are a fast-growing sector of the renewable industry and now provide *ca*.6% of all UK electricity generation (BEIS 2017).

The evidence chain shown in Figure 12 describes the interactions between marine renewable energy developments (hereafter MRED) and seabird populations. Generally, MRED can have adverse effects on marine species through habitat loss or degradation, collision/entanglement, displacement, noise and electromagnetic fields (Inger et al. 2009). The main negative impacts of MRED on seabirds in particular are of two types: collision with turbines and/or infrastructure, and displacement (Drewitt & Langston 2006). Collision causes direct mortality and therefore has an immediate impact on demographic rates and ultimately on population size (Masden & Cook 2016). Displacement occurs when a MRED prevents birds from foraging in their favoured habitats or acts as a barrier to movement of birds intending to forage beyond their preferred area. Thus, by altering the birds' behaviour, MRED can force birds to forage at higher densities in suboptimal habitats, with knock-on effects on their energy budgets and ultimately demographic rates (Fox et al. 2006, Searle et al. 2014). This is particularly important for breeding seabirds that are constrained to obtaining food within a certain distance of their colonies.

Because of the potential risks that they pose to the environment, proposed MRED typically require an environmental impact assessment before consent can be granted (EU 2001, MMO 2017). Due to existing national and international legal protection mechanisms, as well as their high public profile, seabirds are a prominent feature in the environmental impact assessment process associated with MREDs. In this context, three key attributes that affect the seascape's suitability for MRED deployment are the size of local breeding populations, their conservation status and foraging distribution. More specifically, the environmental impact assessment should 1) quantify potential overlap between at-sea distribution of birds from breeding colony SPAs and the location of the proposed MRED, and 2) assess the risks of collision and displacement (and ideally their population-level consequences).

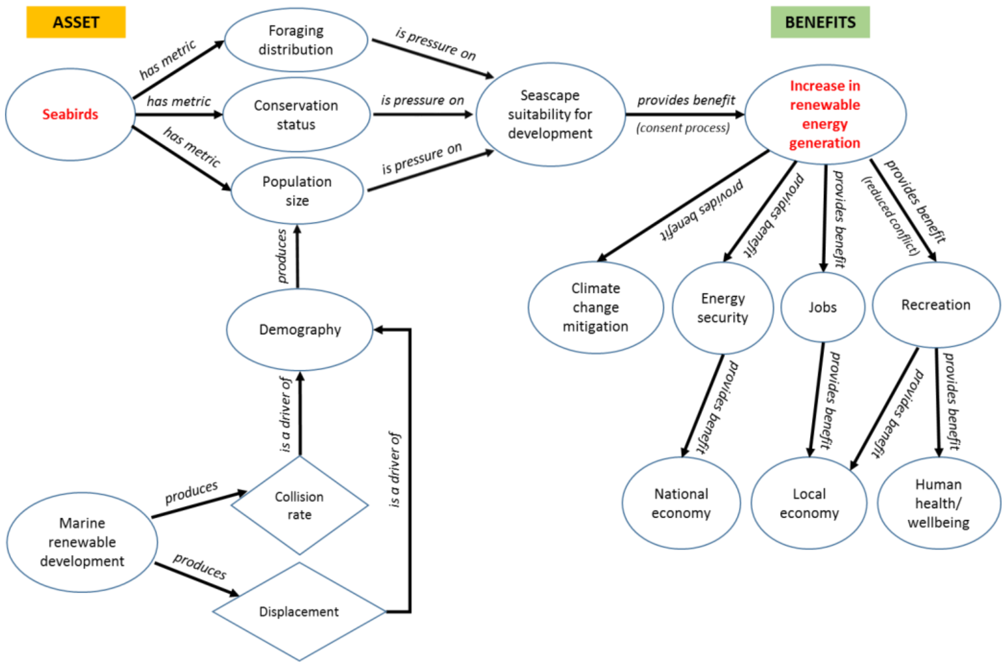


Figure 12: Data graph for conflicts between seabird conservation and the development of renewable energy sources

Figure 13 shows the available scientific evidence for the relationships in the evidence chain for marine renewable energy generation. The key relationships are between:

- MRED and seabird demography (via collision and displacement);
- Seabird demographic rates and population size;
- Seabird population attributes (population size, conservation status, foraging distribution) and location suitability for MRED.

<u>MRED and seabird demography</u>

Our understanding of the impacts of MRED on seabird demographic rates (breeding success and adult survival) is relatively good. Impacts on survival due to collision with marine renewable structures (mainly wind turbines) have been extensively studied (e.g. (Desholm et al. 2006, (Drewitt & Langston 2006, (Furness et al. 2013, (Masden & Cook 2016). Population-level consequences of displacement from offshore wind farms were investigated as part of a previous project carried out by CEH scientists (see Section 5.5.1). The findings indicate that displacement can impact on both breeding success and adult survival ((Searle et al. 2014).

<u>Seabird demographic rates and population size</u>

The relative contribution of adult survival and breeding success to changes in population size were investigated as part of a previous project carried out by CEH scientists (Section 5.5.1). The findings suggest that changes in adult survival have much greater influence on population size than changes in productivity, as predicted for long-lived species (Freeman et al. 2014).

Seabird population attributes and location suitability for MRED

The suitability of locations for proposed MRED and ultimately the success of the consent process is in part determined by their overlap with foraging areas of seabirds, particularly if the birds are members of protected populations. This is governed by European legislation through the requirement for environmental impact assessments for all developments likely to negatively affect birds (EU 2001, Fox et al. 2006).

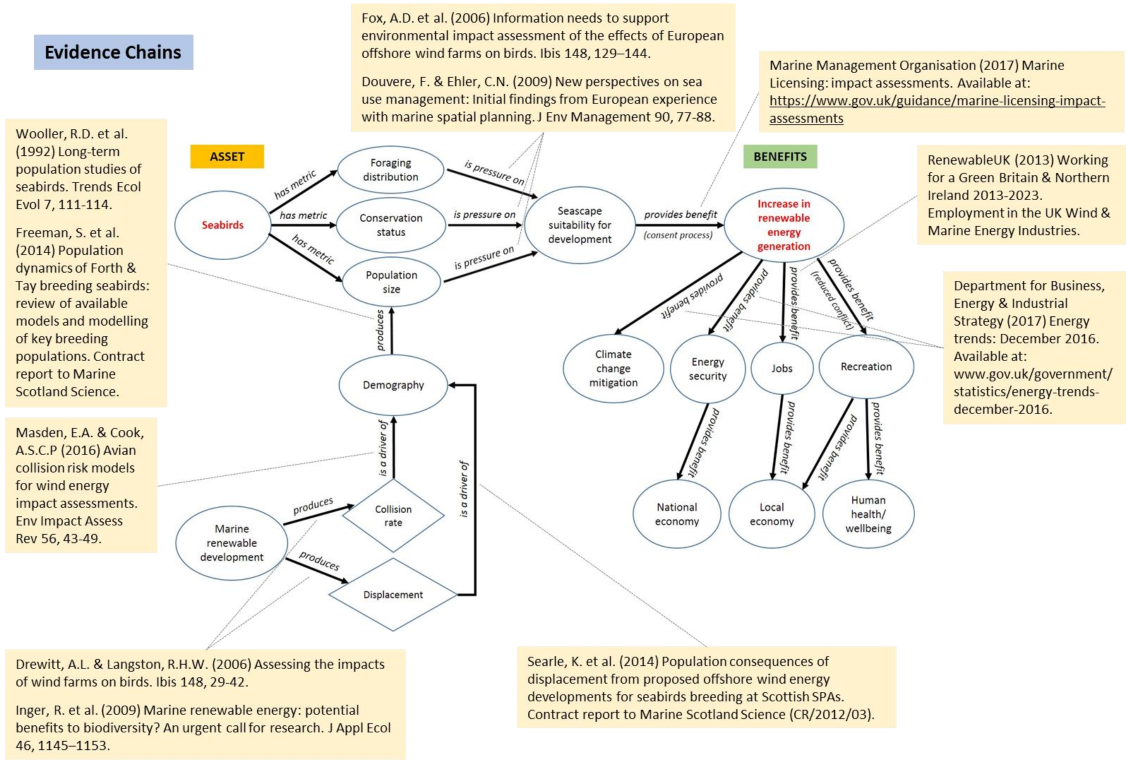


Figure 13: Evidence sources linked to the conflicts between seabird conservation and the development of renewable energy sources data graph

3.6 Air case study – Benefits of trees on air quality and human health

Trees are particularly effective scavengers of air pollutants due to their effect on turbulence (Beckett et al., 2000a, Nowak 2000). Having a higher roughness length (and lower aerodynamic resistance) aids mechanical turbulence and promotes dry deposition to the surface. The deposition velocity is the rate at which a compound deposits to a leaf surface and incorporates both of these aspects of deposition. It is dependent on plant characteristics such as the number of stomata and the leaf area and chemistry of leaf surfaces. Dry deposition rates to trees exceed those to grassland by typically a factor of 3–20 (Gallagher et al., 2002, Fowler et al., 2004).

Several previous studies have shown the effectiveness of trees in capturing pollutants (e.g. $PM_{10/2.5}$) in relation to improving urban air quality. For example Nowak et al. (2014) modelled $PM_{2.5}$ removal by trees in ten US cities and associated health effects. McDonald et al., (2007) modelled the potential of urban tree planting to mitigate PM_{10} across two UK conurbations. Nowak et al. (2006) used meteorological and air pollution data to show the removal of O_3, PM_{10}, NO_2, SO_2, CO by urban trees and shrubs across the United States. Some studies have looked at the suitability and pollutant capture efficiency of particular trees. For example, Beckett et al. (2000b) showed in wind tunnel experiments that coniferous species, and broadleaf trees with hairy leaves, had a greater effectiveness at capturing particles than other broadleaf trees.

The first stage in defining the evidence chains for trees improving air quality was to develop a conceptualisation of the pathways from the Assets (the trees and leaves) to the Benefits (the improved air quality and human health). This data model or ontology describes the relationships (or connections) between entities. Part of the ontology mapping was to define drivers of tree health as well as drivers for human health in the form of air pollutant concentrations. Figure 14 shows the asset as the number of trees in the UK. The relationship between the number of trees and the amount of pollutant removal is well established although the amount of pollutant removal is often dependent on tree species and types of tree, e.g. broadleaf versus conifer or hairy versus smooth leaves. A key driver for the number of trees is the amount of tree planting which is targeted for the UK and set out by the various forestry authorities in England, Scotland and Wales. Trees themselves are not the main component for pollutant removal. Trees in the diagram '*has metric*' leaves. The amount of leaves (or leaf area index, LAI) are key to this process via stomatal uptake of gases and leaf area for interception of particulate matter. This connects with the next entity in the diagram - 'Capture potential' which is a function of the leaves or LAI. This potential '*provides a benefit*' in reducing particulate matter ($PM_{2.5}$) concentrations which in turn can improve human health by improving air quality. Improved health outcomes from the capture of $PM_{2.5}$ by trees can be further monetarised ('*has a value*') into an economic benefit.

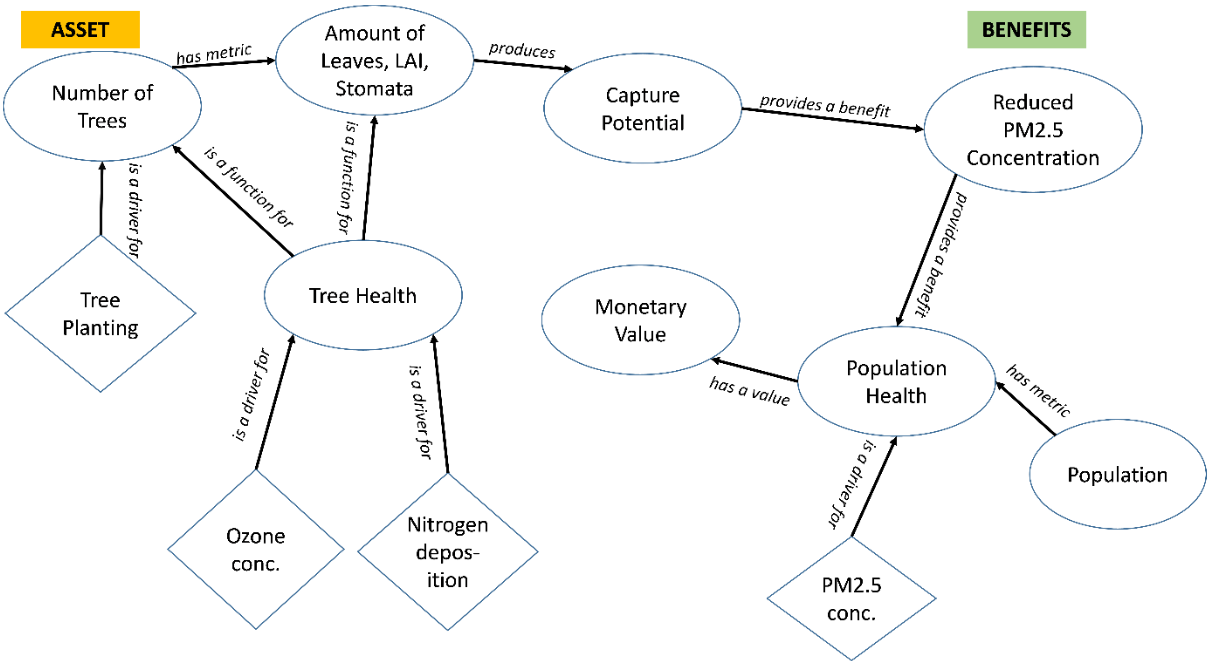


Figure 14: Data graph illustrating pathways for trees improving air quality and human health

Figure 15 shows the available scientific evidence for the relationships or connections in the evidence chains for air quality regulation. Evidence can be divided into three core relationships between:

- pollutant concentrations and tree health;
- leaves/LAI and pollutant capture potential; and
- particulate matter ($PM_{2.5}$) and human health impacts.

<u>Pollutant concentrations and tree health</u>

There are many studies that have researched the impact on tree health from air pollution e.g. ozone and nitrogen deposition.

<u>Leaves/LAI and pollutant capture potential</u>

Research into the capture of air pollutants by trees has primarily focused on particles and nitrogen oxides emitted from transport in urban areas. Research has measured and modelled the increased effect of capturing particles by trees over other vegetation (e.g. grassland). This effect can be 3-20 times more than other vegetation due to the aerodynamic roughness of its structure (e.g. leaves, twigs, branches). In addition, numerous studies have quantified the amount of pollutant capture by trees across urban areas looking at multiple pollutants.

<u>Particulate matter and human health impacts</u>

Links between poor air quality and human health have been well established. Particulate matter of a size <2.5 microns has the capacity to enter through respiratory pathways and enter into the blood stream. Effects of poor air quality are primarily measured in 'deaths brought forward' or increased respiratory hospital admissions. The relationship between concentration and mortality rates has been recommended by COMEAP (the Committee on the Medical Effects of Air Pollution). It is on a large US study which estimated that for every

10 µg/m^3 increase in average $PM_{2.5}$ concentration there is a 6% increase in annual all-cause death rates.

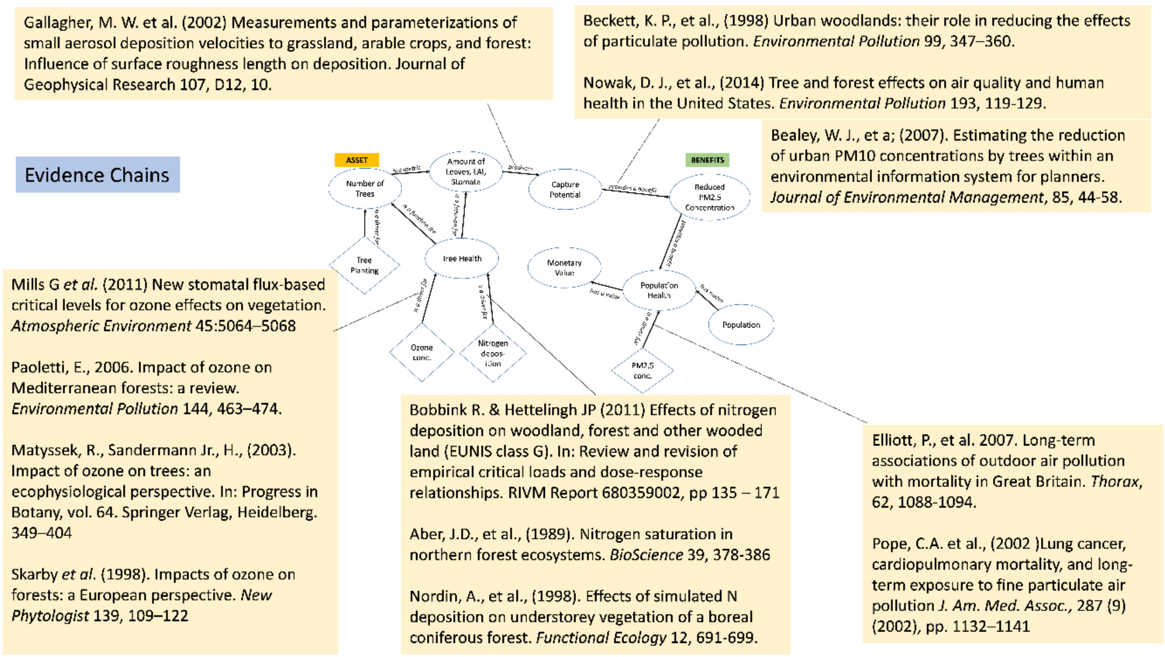


Figure 15: Evidence sources linked to the air quality regulation data graph

4 Data resources and natural capital metrics

Whilst developing the evidence chains described in Section 0, available datasets for the relevant natural capital assets were documented for each of the land, water and air case studies. A full inventory of datasets is provided in Annex 1: Relevant datasets. Datasets and metrics for each of the case studies are summarised in this section.

4.1 Land case study - Pollination

Metrics required for the pollination case study are listed in Table 1.

Table 1: Source and type of natural capital metrics which can be used to assess the service of pollination at the national scale

CEH metrics for pollination service	Source
Bee nectar plant species richness	CS plot data
Broad Habitat type	CS mapped data
Presence of pollinating insect species	BRC (NBN)

To date we have focused only on the CS data in the production of a national natural capital map using the Ecomaps statistical modelling approach (see Section 5). Partly due to resource limitations and timings of staff availability we have made little progress as yet with the next phase of work. However, the following work was started, with BRC staff:

- Provide more detail to the national scale metrics (map) shown in Section 6 by producing a metric at square level which takes into account the actual habitat composition of a square (rather than the just the dominant habitat) and relating it to the values of nectar producing plants produced for those specific habitat types.
- Overlay presence data for pollinator species relevant to their specific target plants.

The plan is to consider the importance of woody linear features in the provision of pollination services based on the potential use of the linear product alongside Land Cover Map (LCM) for producing maps of natural capital metrics. Hedges themselves may be constructed of important pollen producing species (e.g. hawthorn, blackthorn), but they are also important field edge locations for a range of pollen producing species.

Information about data gaps for supporting metrics relevant to this case study is included in Section 0.

4.2 Water case studies

4.2.1 Integrated river, lake and catchment connectivity datasets and tools

Freshwaters are a key component of the UK's Natural Capital. The new UK lakes portal developed by CEH within this project in 2015/16 contains information on >44,000 water bodies that have an area >0.2 ha, and catchment land cover and population information on >14,000 lakes with an area >1 ha. It can, therefore, readily become a significant contributor to a CEH-coordinated natural capital hub. Furthermore, the UK Lakes Portal has recently been integrated into the NBN and BRC's iRecord service, allowing biodiversity records to be searched and/or (species) information on lakes to be uploaded[1]. CEH is also the custodian of the UK river network; this enables questions on river connectivity to be answered and can provide delineated catchments for each 50m stretch. Combining these datasets allows freshwater natural capital metrics to be integrated across freshwater ecosystems, monitoring data from CEH and other networks to be connected, and metrics to be summarised at different catchment scales.

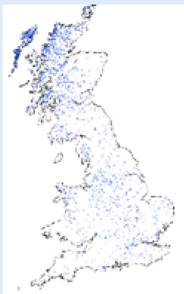
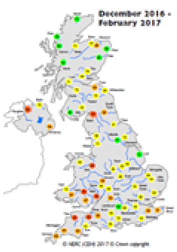
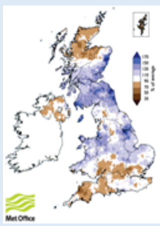
Progress towards these aims has largely been undertaken through closely related CWI projects (i.e. NEC05827 RICT, which is funded by SEPA/EA, etc. and is producing metrics to drive river invertebrate models, and NEC05069 Hydroscape, which is funded by NERC and is developing connectivity metrics across freshwater systems). A suite of Python / GIS tools have been developed to produce a range of metrics across the 50m gridded flow network of the UK; these provide metrics on upstream catchment properties and reach-based attributes. Future development is currently under review following the departure of Filip Kral and the appointment of a replacement member of staff. A list of available metrics is included in the inventory of datasets in Annex 1: Relevant datasets.

[1] http://www.brc.ac.uk/irecord/enter-uklakes-records

4.2.2 Lake water quality regulation

The datasets required for the lake water quality regulation evidence chain are shown in Table 2 and Figure 16.

Table 2: Datasets and metrics relating to the lake water quality evidence chain

Dataset	Entity/Driver *(based on Fig. 16)*	Metric	Map	Notes
UK Lakes data	Lake sensitivity factors (area, volume, depth, flushing rate)			Lake sensitivity factors affect the ecological response of lakes to nutrient inputs.
WFD lake monitoring data	Phosphorus (P)	In-lake P concentration (mg m^{-3})		Available form EA, NRW, SEPA
WFD lake monitoring data	Phytoplankton	In-lake phytoplankton concentrations		Available form EA, NRW, SEPA
Modelled nutrient delivery data	P inputs to lakes	Lake site-specific phosphorus load		Available from ADAS 'SEPARATE' model
CEH land cover map	Land cover type	Nutrient runoff values (kg P ha^{-1} for each land cover type)		Can be converted to nutrient runoff using export coefficients and InVEST water/nutrient delivery model
NRFA river flow data	River flows	Rates of discharge at monitoring points (cumecs)		
Meteorological data	Rainfall	Rainfall over lakes and catchments (mm d^{-1})		

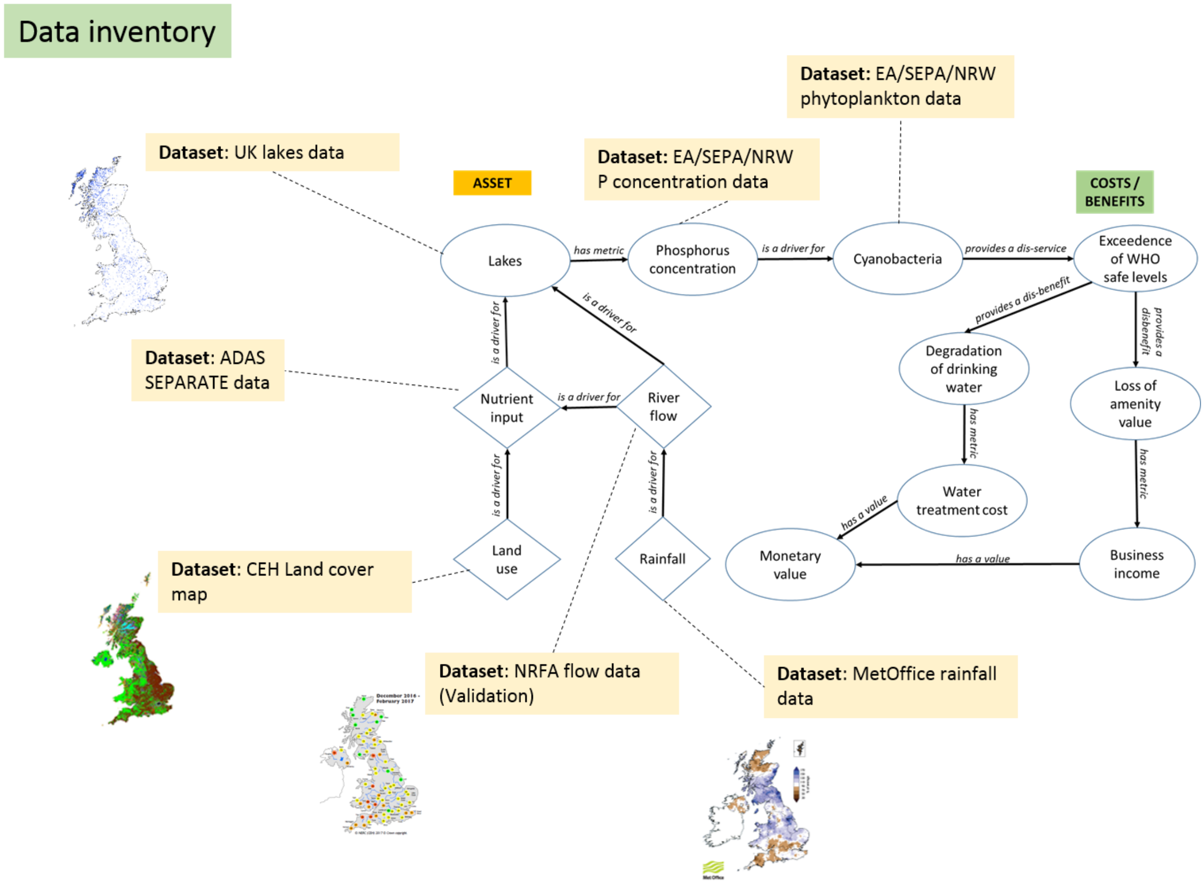
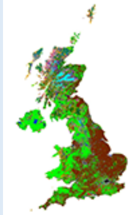
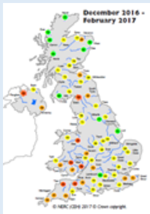
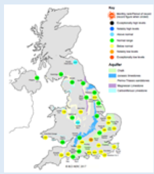
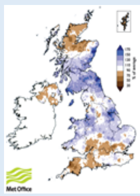


Figure 16: Datasets linked to the lake water quality regulation data graph

4.2.3 Flood mitigation through tree planting

CEH datasets relevant to the flood mitigation through tree planting data graph include the CEH land cover map, Hydrology Of Soil Types (HOST), COSMOS soil moisture and NRFA river flow (Table 3; Figure 17). Additional relevant data are collected and stored by the Met Office and BGS. Together, these data sets provide some of the information required to understand the influence of trees on river flooding. However, in order to convert these data into useful results a model(s) will be required to calculate the temporal dynamic element.

Table 3: Datasets and metrics relating to flood mitigation through tree planting

Dataset	Entity/Driver *(based on Fig. 17)*	Metric	Map	Notes
CEH land cover map	Forest/ woodland cover	Woodland in UK (km^2)		
COSMOS soil moisture	Soil moisture	Volumetric water content (%)		
NRFA river flows	River flows	Discharge at monitoring points (cumecs)		
UK population CENSUS	Population	Number of people per km^2		
BGS groundwater levels	Groundwater levels	Borehole water level data (m)		
Hydrology of soil types (HOST) classes	HOST classes	HOST classes data for 29 soil types; 1km grid.		
Meteorological data	Rainfall	Rainfall over lakes and catchments ($mm\ d^{-1}$)		
Forest planning data	Tree planting	Planned increase/decrease in afforested areas (ha)		

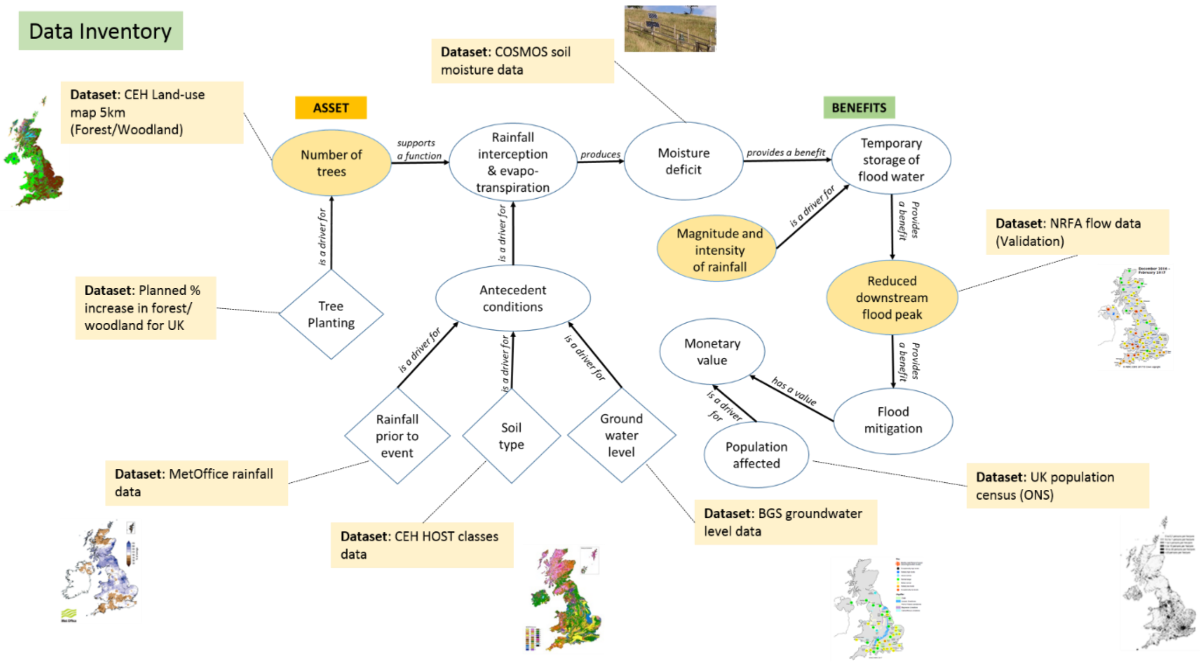


Figure 17: Datasets linked to the flood mitigation through tree planting data graph

4.2.4 Flood and drought mitigation through riverine plants

Datasets that are relevant to the mapping and assessment of assets and benefits relating to flood and drought mitigation by riverine plants are shown in Figure 18. The distribution of aquatic plants in the UK and their relationship to hydrological conditions is based on analysis of the mean trophic rank (MTR) and national river flow archive (NRFA) databases, which comprise many hundreds of sites nationwide. Although the sampling protocols for collecting these data were developed and tested by CEH, most of the data are collected by government agencies.

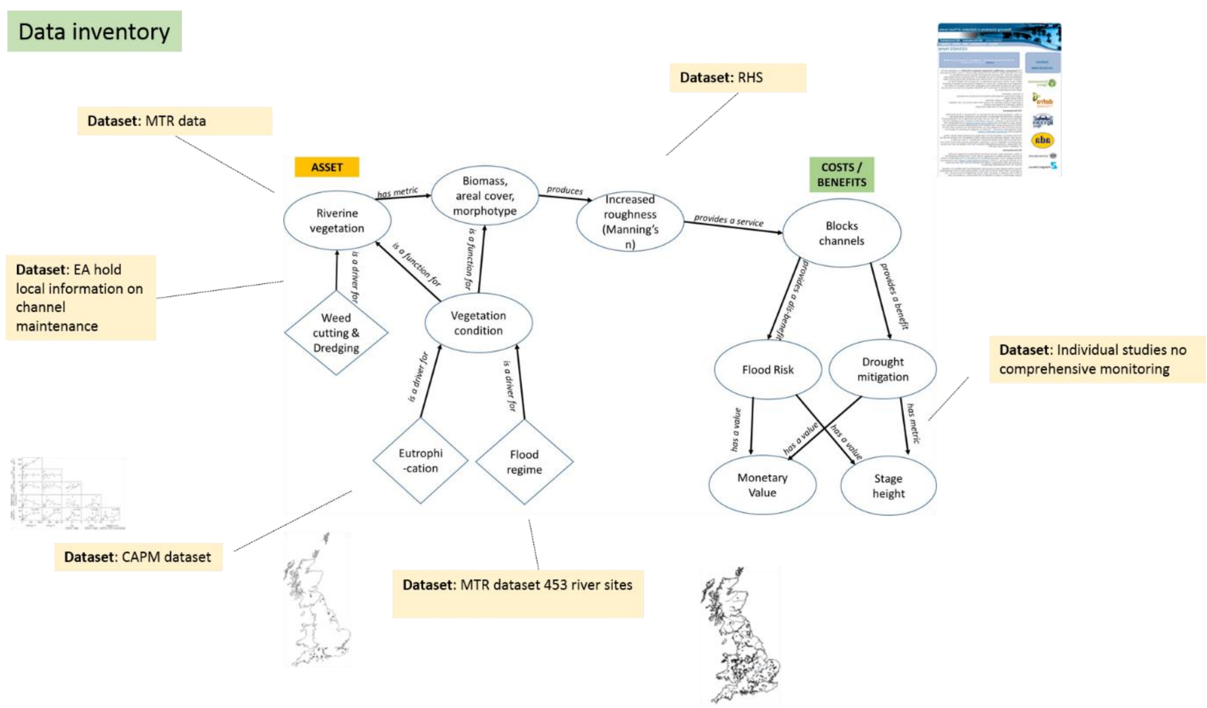


Figure 18: Datasets linked to the drought mitigation data graph

4.2.5 Conflicts between seabird conservation and the development of renewable energy sources

Datasets associated with the case study on marine renewable energy generation are presented in

Table 4 and Figure 19. All listed datasets are at UK scale and are external to CEH. However, most of them are publically owned and the Coastal Seas Ecology Group (Isle of May Long-term Study) has been contributing to several of them (e.g. FAME and STAR, Seabird 2000, Seabird Monitoring Programme), therefore we don't anticipate issues with access for mapping purposes. However, their potential integration into a Natural Capital Portal would need to be negotiated separately with the respective data owners.

Future of the Atlantic Marine Environment (FAME) and Seabird Tracking and Research (STAR) are datasets resulting from a large-scale international seabird tracking project led by the Royal Society for the Protection of Birds (RSPB). They include at-sea location data for multiple colonies of a number of species over several years. Such tracking data obtained from transmitting or archival data loggers are a major contributor to the MRED consenting process as they allow us to establish connectivity between protected seabird colonies (SPAs) and the birds' usage of marine areas considered for development. Access to the data has been requested and we are currently awaiting a response from the RSPB.

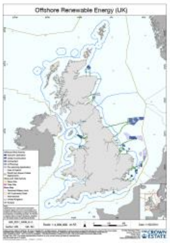
European Seabirds At Sea (ESAS) is a shared international database of at-sea (boat-based and aerial) surveys manged by the Joint Nature Conservation Committee (JNCC). It also contains data for a large number of species over multiple years, however the birds' breeding origin (and therefore potential connectivity to colony SPAs) is unknown. Due to this we are currently considering this a supplementary dataset to the FAME and STAR datasets above.

Breeding colony Special Protected Areas (SPAs) are a subset of SPAs within the full database of strictly protected sites managed by JNCC. The sites are classified for rare and vulnerable birds, and for regularly occurring migratory species in accordance with the European Birds Directive. We have obtained these data and the next step will be to use them in the generation of UK-scale maps.

Seabird 2000 and Seabird Monitoring Programme are led and coordinated by JNCC, in partnership with other organisations. Seabird 2000 contains the results of the latest complete national census of UK breeding seabirds. The Seabird Monitoring Programme (SMP) is an annual monitoring programme of 25 seabird species, at a sample of breeding colonies throughout the UK and Ireland. The data on breeding numbers and breeding success of seabirds are used to assess their conservation status. We have obtained these data and the next step will be to use them in the generation of UK-scale maps.

The Crown Estate Offshore Renewable Energy dataset contains the location and spatial extent of offshore wind farms (grouped into the following categories: in operation, under construction, consented, in planning, in pre-planning application, area of search for future developments) as well as tidal and wave sites. We have obtained GIS shape files with these data and the next step will be to use them in the generation of UK-scale maps.

Table 4: Datasets relating to the conflicts between seabird conservation and the development of renewable energy sources data graph

Dataset	Entity/Driver *(based on Fig. 19)*	Metric	Data Map	Notes
FAME and STAR GPS tracking	Seabirds	Foraging distribution (GPS fixes)	To follow	External dataset (RSPB)
Modelled foraging distribution based on FAME/STAR data	Seabirds	Foraging distribution (density)	To follow	External dataset (RSPB)
ESAS at-sea surveys	Seabirds	At-sea distribution (transect surveys)	To follow (if data are used)	Supplementary external dataset (JNCC); to be used in conjunction with tracking datasets if necessary
Breeding colony SPAs	Seabirds	Conservation status	To follow	External dataset (JNCC)
Seabird 2000 and Seabird Monitoring Programme	Seabirds	Population size (AON/number of individuals)	To follow	External dataset (JNCC)
Offshore renewable energy UK	Marine renewable development	Location; Spatial extent		External dataset (The Crown Estate)
Employment across marine renewable energy sector	Renewable energy generation	Number of jobs created		External dataset (RenewableUK)
Energy trends	Renewable energy generation	Cumulative installed capacity (MW); Energy generation (GWh)		External dataset (UK Government - BEIS)

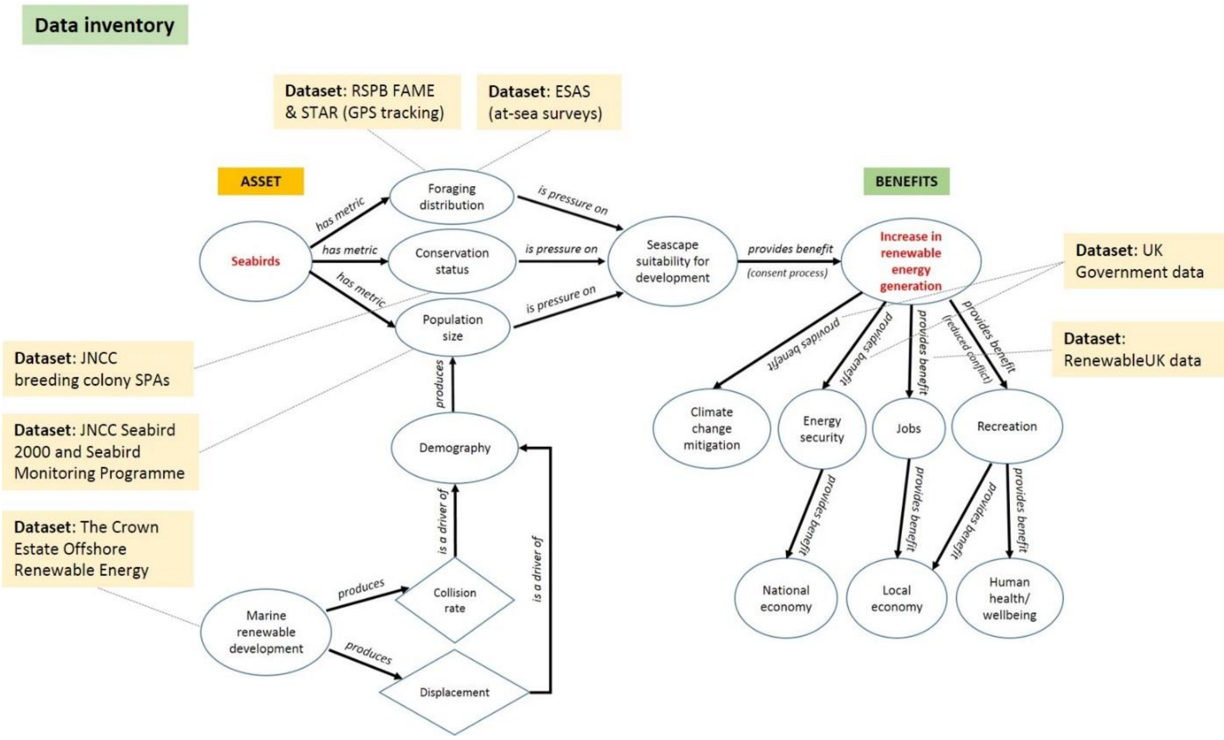


Figure 19: Datasets relating to the conflicts between seabird conservation and the development of renewable energy sources data graph

4.3 Air case study – air quality regulation

4.3.1 Natural capital metrics

There has been a focus on defining and quantifying natural capital metrics related to '**air pollution regulation**'. This is defined as the function that vegetation provides in removing air pollutants from the atmosphere, thereby reducing pollutant concentrations and as a result, exposure of the population. This reduced exposure has direct health benefits through avoided mortality and morbidity which can be valued economically.

Similar to the evidence chains shown in Section 0, SEEA has produced logic chains linking ecosystem attributes to ecosystem services, benefits and values. The SEEA methodology identifies metrics of natural capital extent, but also attributes which define the ability of that natural capital to provide services. The attributes which underpin the ability of natural vegetation to remove air pollutants (fine particulate matter $PM_{2.5}$, ozone (O_3), nitrogen compounds (e.g. nitrogen dioxides, NO_2) and sulphur dioxide (SO_2) include leaf surface area, vegetation type and structure, and interactions with other pollutants and meteorology. These are summarised in Figure 20. Note that SEEA list the relevant attributes but not their inter-relationships to produce the ecosystem service as shown in the Section 0 evidence chains.

Using the same methodology, we have also assessed other ecosystem services not obviously captured under other categories including '**regulation of noise by vegetation**' and '**local thermal regulation**' within urban areas. Asset diagrams are shown below for noise regulation and thermal regulation (Figures 21 and 22 respectively) which list the ecosystem characteristics or metrics of relevance to these services.

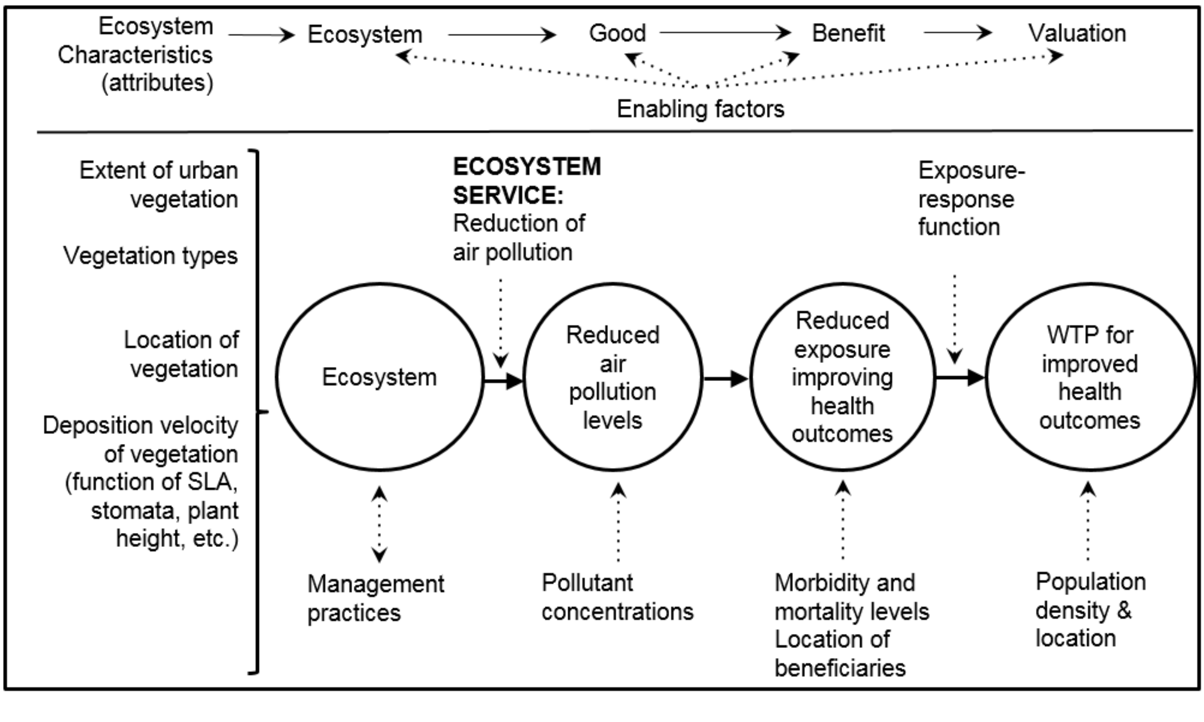


Figure 20: SEEA natural capital asset diagram for 'removal of air pollution by vegetation' incorporating logic chain to final service delivery and valuation

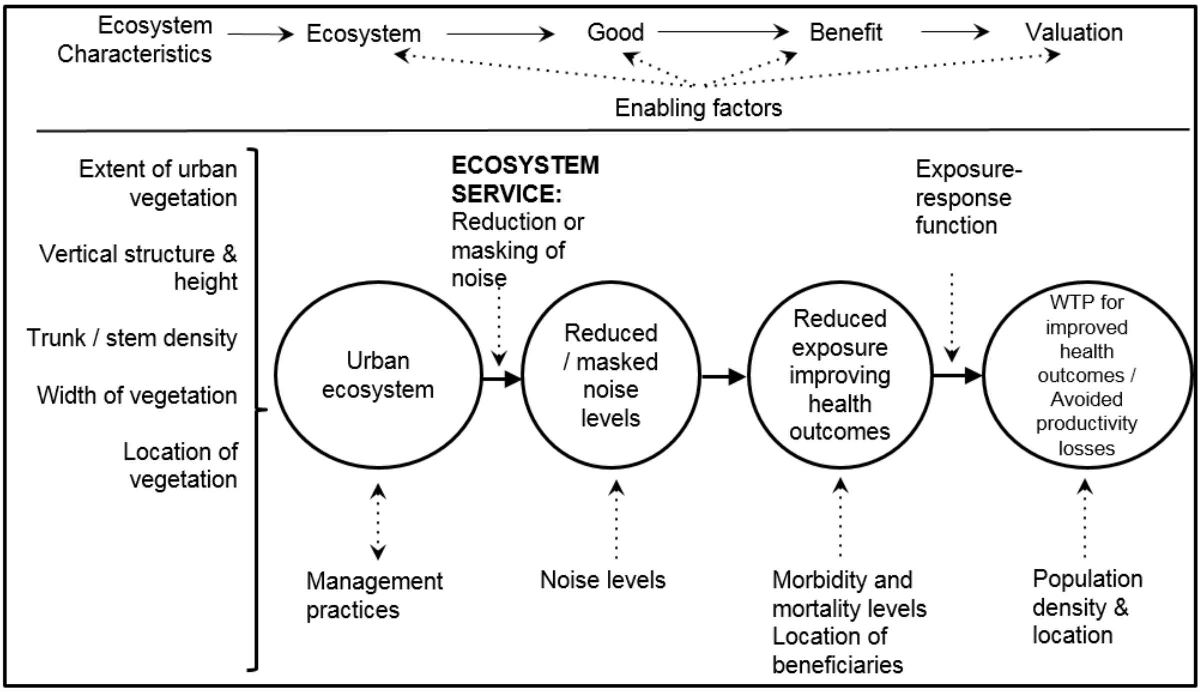


Figure 21: SEEA Natural capital asset diagram for 'noise regulation by vegetation' incorporating logic chain to final service delivery and valuation

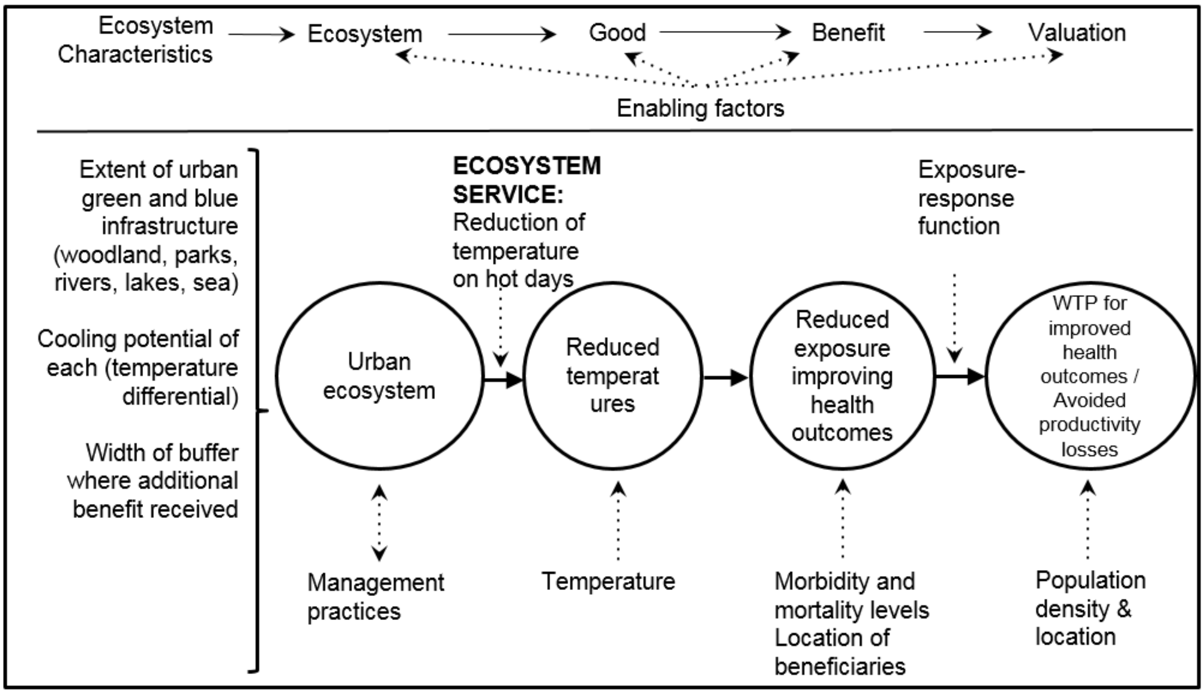


Figure 22: SEEA Natural capital asset diagram for 'local temperature regulation by vegetation' incorporating logic chain to final service delivery and valuation

4.3.2 Natural capital indicators/datasets

The datasets identified relate to the natural capital itself, as well as some of the intermediate steps in the service delivery. These are summarised below for air quality regulation, noise regulation and local temperature regulation. In all cases, the detailed data required to model this at a fine scale involves much more complex inputs. Where these are available, e.g. to run national scale models, it may also be possible to list and map those inputs. However, these are not always available at the UK scale and may not be essential for mapping the underpinning natural capital.

Air quality regulation

- Area of broad habitat types
- Look up table of deposition velocity of each broad habitat type (by pollutant).

Noise regulation

- Area of vegetation which is able to provide a noise reduction service, defined by a specific set of attributes (ideally to include location, horizontal and vertical structure)
- Look up table of noise reduction provided by each vegetation type classified by its attributes
- OS Mastermap, in combination with CEH Land Cover Map 2007 and Bluesky's National Tree Map may be sufficient to identify candidate urban vegetation providing a service.

Local temperature regulation

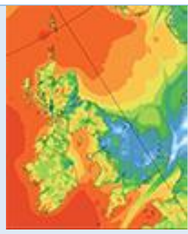
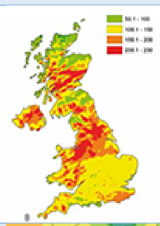
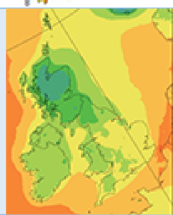
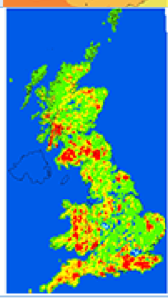
- Area of parks, woodland, and other natural land cover types (including water bodies) which can provide urban cooling function on hot days (from CEH Land Cover Map 2007, and OS Mastermap)
- Look-up table of temperature differentials, by vegetation type.

Datasets specifically associated with the case study on air quality regulation by trees are provided in Table 5 and Figure 23. Table 5 shows the datasets that can be used to derive and quantify metrics in the Asset to Benefit chain (as shown in Figure 23). Many of the metrics required along the chain to assess the effect of trees on human health are from modelled data using an air dispersion model (EMEP4UK). This model provides annual average concentrations for the UK for a number of pollutants including $PM_{2.5}$.

Calculating the reduction in the concentration of $PM_{2.5}$ from trees can be modelled using the difference between two model runs using land cover maps – one run with no trees and one run with trees. Spatial variability in reduction across the UK are accounted for not only by the distribution of trees in the UK, but also by factors affecting deposition velocity which is largely governed by the wind speed pattern due to orography. The relationship between $PM_{2.5}$ and human health effects have largely been quantified by hospital admissions and mortality burden of long term exposure. $PM_{2.5}$ related data on hospital admissions are centred on respiratory and cardiovascular admissions.

The economic evaluation of air pollution impacts on human health is applied through damage costs. Damage costs give an estimate to the cost to society of a change in each additional tonne of pollutant emitted. Conversely they can be used to assess a benefit (e.g. the effect of trees) to society by reducing a certain pollutant by one tonne. For $PM_{2.5}$ the damage costs are dominated by long term mortality burden and are based on a relative risk of 6% per 10 $\mu g\ m^{-3}$ change. This percentage change describes the relationship between a change in $PM_{2.5}$ and a change in the age-specific mortality rate, which, in turn, leads to changes in life expectancy. Damage costs for PM are set out in the notes in Table 5.

Table 5: Datasets relating to the role of trees in regulating air quality

Dataset	Entity/Driver *(based on Fig. 23)*	Metric	Data Map	Notes
CEH Land Cover Map 2007 (Forest/Woodland)	Number of trees	Area (ha) of woodland in the UK		
Planned % increase in forest/woodland for UK	Policy targets for increased tree planting	Target area (ha) to be planted by 2050		Different targets on planting exist between the four UK countries
Modelled ozone concentration for the UK at spatial resolution of 5x5 km (resp. 1x1 km) grid squares	Ozone concentration	Concentration (ppb) for every grid square. Based on a 3-5 year average.		Can be compared with ozone critical level for trees of AOT40[2] (April to September) 5000 ppb hours
Modelled N deposition for the UK 5km (1km) grid squares	Nitrogen deposition	Depostion (kg N ha^{-1} yr^{-1}) for every grid square. Based on a 3-5 year average.		Can be compared with empirical nutrient nitrogen critical load of 10-20 kg N ha^{-1} yr^{-1}
Modelled $PM_{2.5}$ for the UK 5km (1km) grid squares	$PM_{2.5}$ concentration	Concentration (µg m^{-3}) for every grid square. Based on a 3-5 year average.		Can be compared with air quality limit of 10 µg m^{-3}. (WHO, 2006)
Calculated % reduction in $PM_{2.5}$ for the UK 5 km (or 1 km)	Reduced $PM_{2.5}$ concentration	% reduction per grid square.		
Reduced number of hospital	Population health	Admitted patients		The concentration-response is a 6%

[2] Accumulated Ozone over a Threshold of 40 ppb

Dataset	Entity/Driver *(based on Fig. 23)*	Metric	Data Map	Notes
admissions & mortality				change in mortality per 10 µg/m^3 change in mean airborne $PM_{2.5}$ (COMEAP, 2009)
Damage costs of PM	Monetary value	PM damage costs per tonne		Central value: Transport: £58,125 Industry: £30,225 Domestic: £33,713
Population data: UK CENSUS	Population	Persons ha^{-1} per grid square		

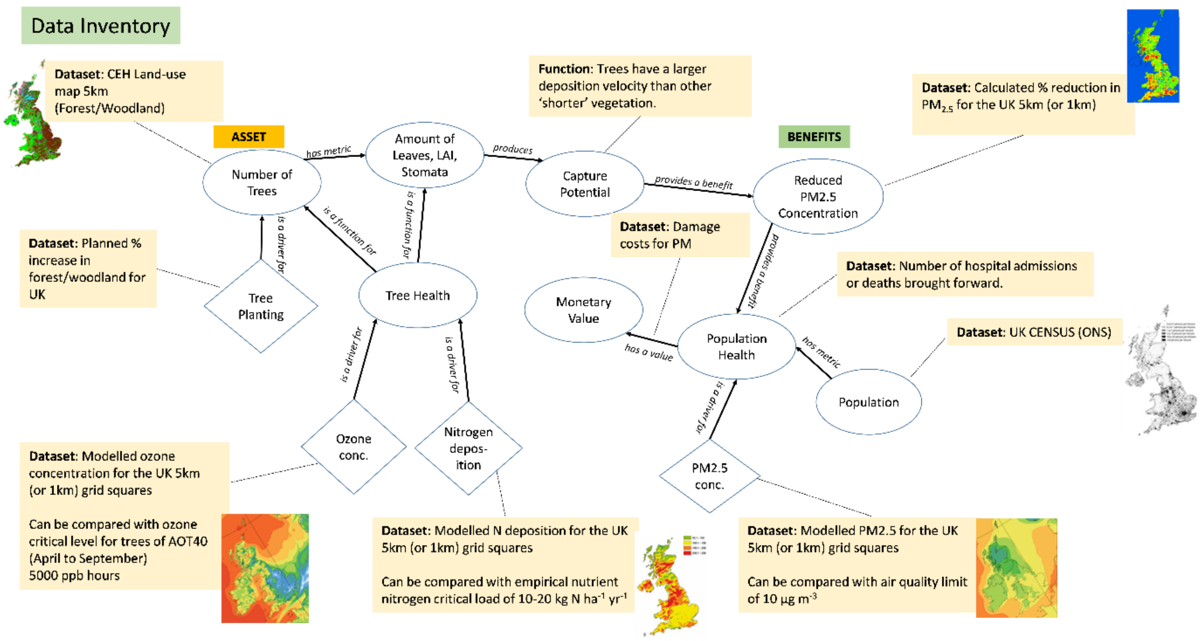


Figure 23: Datasets relating to the role of trees in regulating air quality data graph

5 Models: development and application

5.1 Introduction

Working in collaboration with ongoing initiatives within CEH to collate and describe models within a model catalogue, we have collated available information about models that have relevance to natural capital and ecosystem services. The ongoing CEH work in this area builds on an earlier model catalogue produced under the SIMDAT project NEC04222 (Rowe et al. 2012), and more recent activities as part of the Defra-funded Catchment Management Modelling Platform, recently launched as CAMMP, and the NC models project PIMMS. PIMMS, working with BGS to ensure harmonisation with their model cataloguing, focused primarily on designing the structure and information fields required to adequately catalogue models and to design a flexible and searchable web interface to host them. There is not yet a definitive list of CEH models, or the metadata associated with them. The information presented below should be seen in this context, and viewed as a first attempt to catalogue information about models owned by and/or used by CEH that can tell us something about natural capital and/or ecosystem services. The models are related to the land, water and air case studies in Section 5.5.

5.2 Methodology

Recent lists of CEH and other models were obtained. These lists represent key models produced or owned by CEH, and in some cases external models used in application by CEH, or in partnership with CEH. This list was supplemented with other models that CEH produces, or that CEH adapts or uses. To maximise efficiency and minimise duplication, five key fields were extracted from the developing model catalogue (Rows 1-5, Table 6 below). While the CEH model catalogue fields are not yet finalised, these fields were deemed relatively stable. Six additional fields were added to provide information on natural capital, in line with the creation of evidence chains, and with a view to tagging or linking models to components of those evidence chains (Rows 6 to 11, Table 6).

When tagging models with links to the evidence chain, the following definitions were adopted:

- **Natural capital stocks:** Outputs quantify only the stocks of natural capital, although input variables may have wider scope.
- **Natural capital processes and stocks:** The model simulates processes and stocks of natural capital, or both can be obtained as intermediate outputs from the model.
- **Ecosystem services potential:** The model simulates the amount of service that is available for use by humans, regardless of whether it is actually utilised or not, e.g. flood regulation in an uninhabited catchment
- **Ecosystem services realised:** The model simulates some measure of the service that is actually used by humans. Primarily for cultural services where the service is measured by the number of people conducting an activity, or for provisioning services where the service is measured as a quantity harvested or extracted. This field can also be relevant for regulating services, where the service can be attributed to a population or set of beneficiaries.

- **Benefit:** The model simulates some measure of benefit, e.g. improved health outcomes, reduced stress, flooding avoided.
- **Trade-offs:** Whether the model itself conducts or visualises trade-off analysis or interpretation.

Table 6: Data entry fields to record information on CEH models relevant for natural capital and ecosystem services

Row	Field name	Data entry instructions
1	Model name	Including acronym if any (spell out acronym)
2	Primary purpose	Short phrases only; e.g. predict catchment nutrient loss, simulate pesticide transport, pollution source apportionment, etc.
3	URL / website for model	This should be the outward facing public site for the model
4	Contact / Owner	Person & Organisation (& URL)
5	Application scale	Choose one or more: 1) plot, 2) field, 3) farm, 4) river reach, 5) catchment, 6) landscape, 7) regional, 8) national
6	CEH owned	Yes / No / Partly (give details if applicable)
7	Entered by	Name
8	Natural Capital	Natural Capital - stocks only; Natural Capital - processes & stocks; Ecosystem Service - potential; Ecosystem Service - realised; Benefit; Trade-offs
9	Natural Capital / Ecosystem Service (coded)	1) Natural capital stocks; 2) Natural capital stocks & processes; 3) Ecosystem services potential; 4) Ecosystem services realised; 5) Benefit; 6) Trade-offs
10	Natural Capital Components	Harmonise to set keywords/phrases
11	Ecosystem Services & biodiversity	Harmonise to set keywords/phrases

5.3 Overview of models

Natural capital is defined as “the stock of natural assets which include geology, soil, air, water and all living things. It is from this natural capital that humans derive a wide range of services, often called ecosystem services, which make human life possible”. Therefore all models in CEH should tell us something about one or more parts of the evidence chain from natural capital assets to ecosystem services and human benefits. The majority of models focus on either natural capital stocks or processes, rather fewer tell us something about ecosystem services, and only a handful tell us about benefits to humans. The working list of CEH models and their links to natural capital and ecosystem services are shown in Annex 3: Model/tool catalogue.

There are subtleties in the distinction between whether an ecosystem service is considered as only potential or whether it is realised. There are also grey areas between what might be considered a benefit and what is a service. The wider ecosystem services community has not yet reached consensus on these definitions, although the international SEEA accounting system is providing guiding principles relevant from an economics perspective. As a result, the categories and tags assigned to CEH models may need to be revised.

5.4 Information on selected models

We provide additional detail on a few individual models here as examples, which link to multiple components of the evidence chain.

5.4.1 LUCI - Land Utilisation & Capability Indicator

About the model

The LUCI (Land Utilisation and Capability Indicator) model (Sharps et al. 2017) is a second-generation extension and software implementation of the Polyscape framework, as described in Jackson et al. (2013). LUCI models a variety of ecosystem services: agricultural productivity, habitat, carbon sequestration and the mitigation of flood risk, diffuse pollution and erosion. Ecosystem service condition is assigned based on nationally available datasets (enhanced with local data, where available) on topography (raster DEM), stream network (vector polyline format), precipitation and evapotranspiration (raster format), land cover and soil type (vector polygon format).

These are linked to lookup tables and processed within the model, with simulation of connectivity through cost distance approaches for habitat and topographic routing for hydrological and associated services. The topographic routing approach enables explicit simulation of movement of water and diffuse pollution over the landscape, as well as identification of features which help to mitigate risk of flash flood and in-stream pollution. The model runs at the catchment scale with a fine resolution, enabling assessment of the impact of farm scale interventions. The model also identifies opportunities to improve ecosystem service condition, and these output maps can be used for decision support. Trade-offs and synergies between individual service provisions are modelled explicitly to support such decision-making.

LUCI covers stocks and processes linked to service provision, and provides outputs on a range of ecosystem services. These are mostly potential services since they do not take account of benefitting populations, or otherwise account for actual service use. Actual service use is partly addressed by the carbon module which calculates a metric of carbon sequestration, depending on whether soil carbon stocks are in equilibrium with current land use.

Case study: Ecosystem service benefits of uptake of the Glastir agri-environment scheme

Modelling of projected impacts of uptake of the Glastir scheme as of 2016 identified numerous benefits (Table 7, Figure 24). These included a reduction in flood risk and diffuse pollution, and an increase in carbon storage and area accessible to broadleaved woodland species. Some trade-offs may be anticipated in the form of a reduction in agricultural productivity on land where the intensity of farming was reduced and land was taken out of production for afforestation and creation of buffers. Output from the LUCI model suggests that this took the form of 4451 ha which were downgraded from high and very high production to moderate production or less. However, it is unlikely that highly productive land would have been selected to go into these elements of the scheme, so losses in terms of agricultural output may be relatively low. The total area of benefits is around four times the total area of reduced productivity, indicating that benefits are provided to areas outside the area where land cover change takes place. Furthermore, multiple benefits are projected for many of the Glastir interventions.

Table 7: Modelled change in ecosystem services as a result of Glastir uptake

Service	Projected change in ecosystem service or quality	Percentage change
Carbon storage in vegetation and top 1m of soils	Average of 2.5 t yr^{-1} sequestration over 150 years	0.074 % increase once soils have reached equilibrium
Area accessible to broadleaved woodland species	12674 ha increase (plus habitat increase of 3923 ha)	2.8% increase
Area of “mitigating” land: this is the area classified as increasing infiltration into soil, which can help reduce the risk of flash floods and water quality issues	4120 ha increase	0.97% increase
Area of “mitigated” land for flood and diffuse pollution: this is the area upslope of mitigating land, which benefits by being less connected to the watercourse	11641 ha increase	3.25% increase
Area of land “accumulating flow”: this is the area where the topography of the land concentrates runoff water increasing the risk of flash flood	6066 ha decrease	1.6% decrease
Mean in stream N concentration	0.013 mg/l reduction	0.52% decrease
Mean in stream P concentration	0.001 mg/l reduction	1.55% decrease
Agricultural intensity	4451 ha downgraded from high and very high production to moderate production or less	0.44% of high and very high production land was downgraded

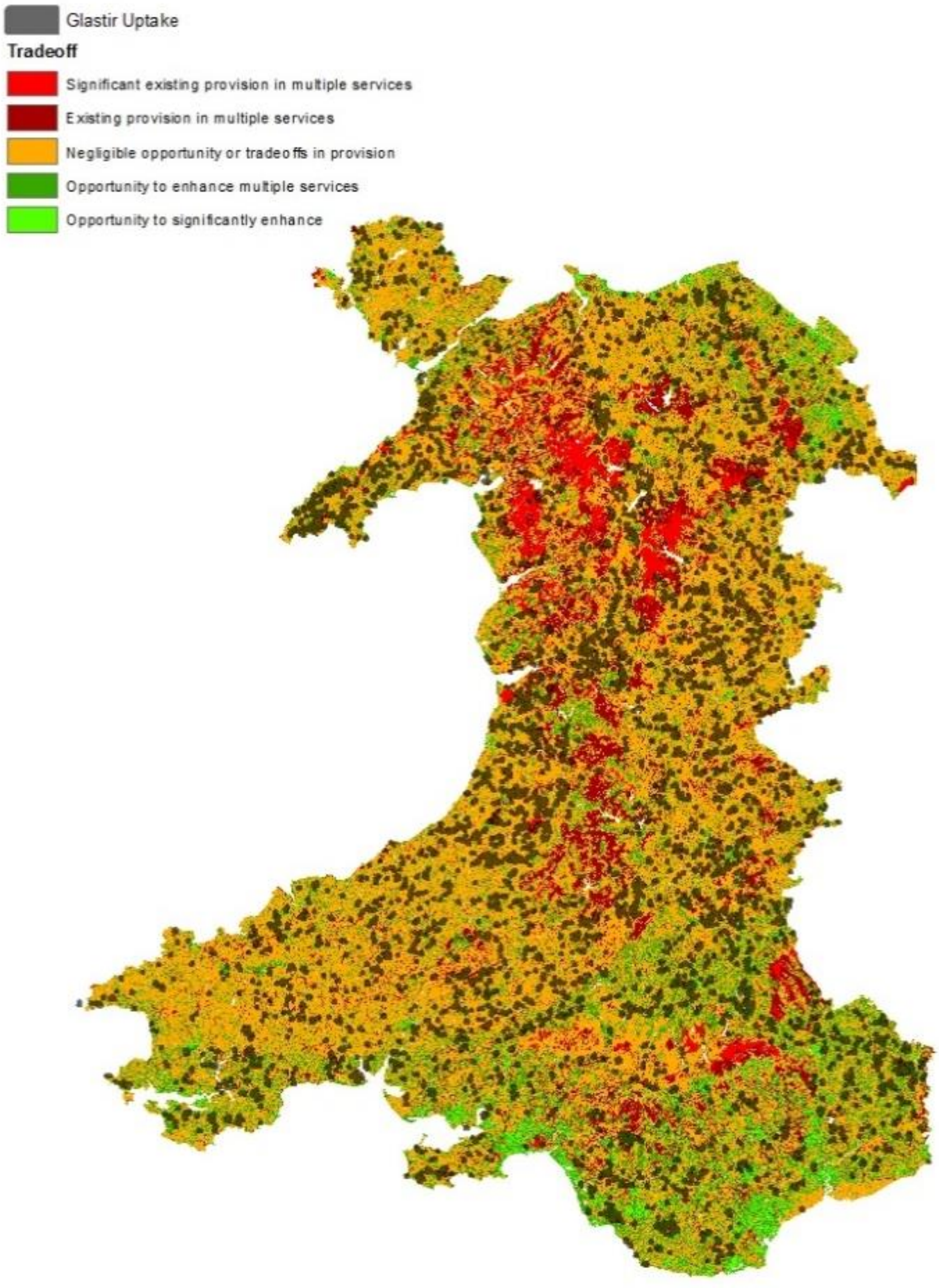


Figure 24: Glastir uptake mapped over trade-off output for baseline conditions, with a buffer for anonymity and visibility purposes

5.4.2 EMEP4UK

About the model

The EMEP4UK model is an atmospheric chemistry transport model. It incorporates aspects of chemical transport and transformation, and dynamic interactions with meteorology and land cover on a sub-daily basis. It is capable of representing UK atmospheric composition in greater detail than larger, i.e. European-scale models, with the ability to simulate hourly air pollution interactions over decadal time scales using a 5km grid or finer, down to 2km. The Weather Research Forecast (WRF) model is used as the main meteorological driver.

The current operational version of EMEP4UK is rv4.4, based on the EMEP MSC-W rv4.4 (Simpson et al. 2012) which is currently used to support European policy development by the UNECE Convention on Long-range Transboundary Air Pollution (CRLTAP) and the European Commission. The model core code is open source and available for download from the EMEP website. EMEP4UK is thus an ideal tool to analyse the impact of policies in the UK, with the benefit of higher resolution which is critical to account for the spatial allocation of wet deposition.

EMEP4UK simulates hourly to annual average atmospheric composition and deposition of various pollutants, including PM_{10}, $PM_{2.5}$, secondary organic aerosols (SOA), elemental carbon (EC), secondary inorganic aerosols (SIA), SO_2, NH_3, NO_x, and O_3. Both dry and wet deposition of pollutants are calculated. In the model, PM2.5 concentrations from both primary and secondary sources are calculated based on primary industrial and agricultural emissions of precursor compounds within the UK, import of precursors from abroad via hemispheric transport as well as VOC emissions from vegetation and other sources.

EMEP4UK covers stocks and processes linked to air quality, and can provide outputs on pollutants removed, by vegetation type, as well as change in concentration (which governs exposure of the population to air pollution). It only partially addresses the realised service, since it does not explicitly calculate a population-weighted exposure, but the realised service can easily be calculated from the outputs.

Case study: Modelling pollutant removal by vegetation for the UK natural capital account

EMEP4UK is being used to improve estimates of pollutant removal by vegetation for the UK Office of National Statistics. The previous estimates of this service were done on gridded data, but did not take account of the dynamic nature of deposition velocities, which is dependent on interactions with other pollutants and meteorology, and is variable over time. Since EMPE4UK is also a transport model, it incorporates pollutant transport, thus separately identifying where the service is provided and where the benefits may be realised.

Interim mapped outputs are shown in Section 6 on national scale maps linked to the evidence chains. Table 8 and Table 9 provide interim results to demonstrate what is possible. These data can then be analysed in terms of reduced exposure of the population to air pollution, and hence to calculate an economic value arising from the avoided mortality and morbidity.

Table 8: Estimated pollutant uptake by GB vegetation (kt pollutant yr^{-1})

	EMEP4UK
PM_{fine}	9.97
SO_2	29.62
NH_3	31.28
NH_4^+	2.33
NO_3^-	4.07

Table 9: Average concentrations simulated with the EMEP4UK model (µg m^{-3})

Pollutant	Current land cover	No vegetation	Absolute difference	Relative difference
PM_{fine}	4.70	5.47	-0.77	-14%
SO_2	0.81	1.10	-0.29	-26%
NH_3	1.28	1.58	-0.30	-19%
NO_2	5.35	5.36	-0.005	-0.1%
O_3	68.20	77.70	-9.50	-12%

5.5 Linking models to evidence chains

The models described above and included in the model catalogue (Annex 3: Model/tool catalogue) have been linked to the case study evidence chains for the land, water and air systems.

5.5.1 Water case studies

Lake water quality regulation

Figure 25 indicates some of the models that could be used to link nutrient (especially P) inputs to lakes and in-lake concentrations of P and cyanobacteria; however, it is recommended that the extent and availability of other suitable models is explored further.

The OECD (1982) model is a very simple model that works on an annual timescale and has been derived empirically from data collected from a large population of lakes. The model that links P concentration to likelihood of cyanobacterial blooms (Carvalho et al., 2013) is similarly derived. Neither of these models incorporates any process based understanding and may not represent the impacts of future changes on lakes accurately, especially when these are driven by concurrent changes in multiple pressures.

CEH has a more process based lake response model (PROTECH) that could be used for this purpose. However, whilst PROTECH generates more frequent (daily) values for in-lake chemical and biological water quality, and more details of the types of biota likely to be produced, these outputs are driven by inputs of soluble nutrients from the catchment, only. These inputs do not include particulate P, i.e. the P that is bound to eroded soil particles and likely to increase in terms of delivery to the lake under climate change in relation to extra energy in storm events eroding more soil from the catchment. In addition, we have little understanding of how much of the P that has been adsorbed onto these eroded soil particles becomes soluble again (and therefore available to algae for growth) once those particles have entered a waterbody, or over what timescale that transformation may take place. These questions can only be answered by monitoring a small number of lakes and catchments in detail under future change conditions. There are few existing datasets that meet this need.

The ADAS SEPARATE model is a nutrient source apportionment model that can be used to predict nutrient runoff from catchments to lakes on an annual basis. The model is held by ADAS, but it has been run for England and Wales already and there are plans to include Scotland, too. It would be possible to incorporate output from this model to estimate the annual delivery of nutrients to lakes from their catchments; indeed this has already been completed within the Defra Toolkits project (NEC04658; May et al., 2016). There are several other models that could be used for this purpose. These include the InVEST water and nutrient delivery models (Sharps et al., 2016; Redhead et al., 2016), which CEH have been calibrating and testing for use in the UK. However, none of these models can provide seasonal or more frequent nutrient delivery data. As such, they are unable to predict the impacts of climate change (especially storm events) on nutrient delivery to lakes. More research is needed in this area.

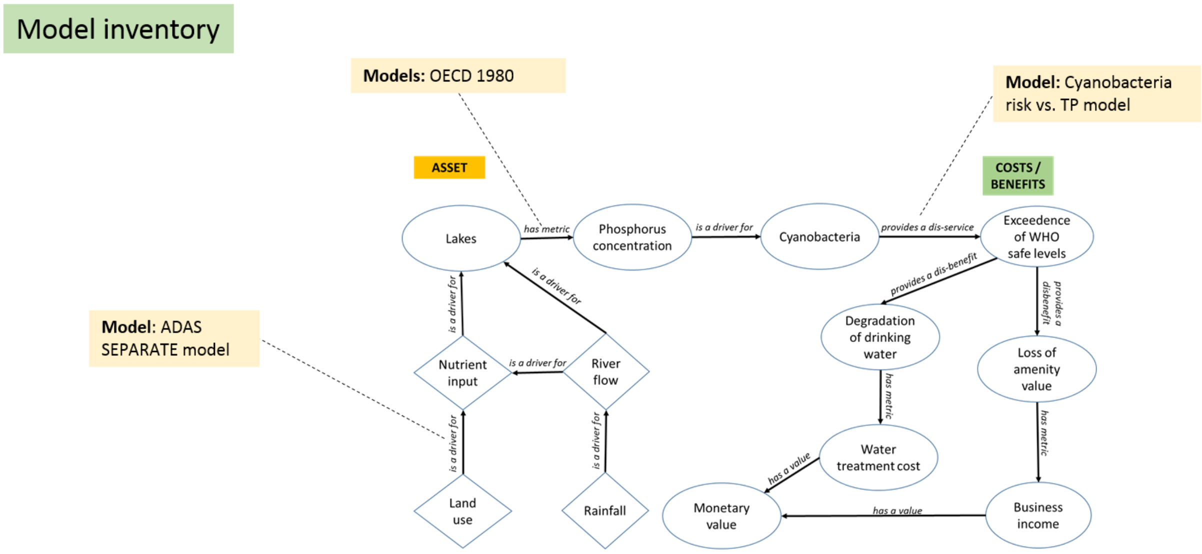


Figure 25: Models linked to the lake water quality regulation data graph

Flood risk and drought mitigation by riverine vegetation

Figure 26 shows the models that can be used to link the various components of the evidence chain between riverine vegetation and flood/drought mitigation. The Conveyance Estimation System is a model that calculates the amount of water a channel can convey safely. Within the model environment, river engineers can include the effects of vegetation. The model allows the user to input the location of their river system and, by trawling through national datasets, identify the most likely forms of plant growth present. It uses another national dataset for this task, the River Habitat Survey dataset, which includes thousands of sites and, again, was designed in part by CEH.

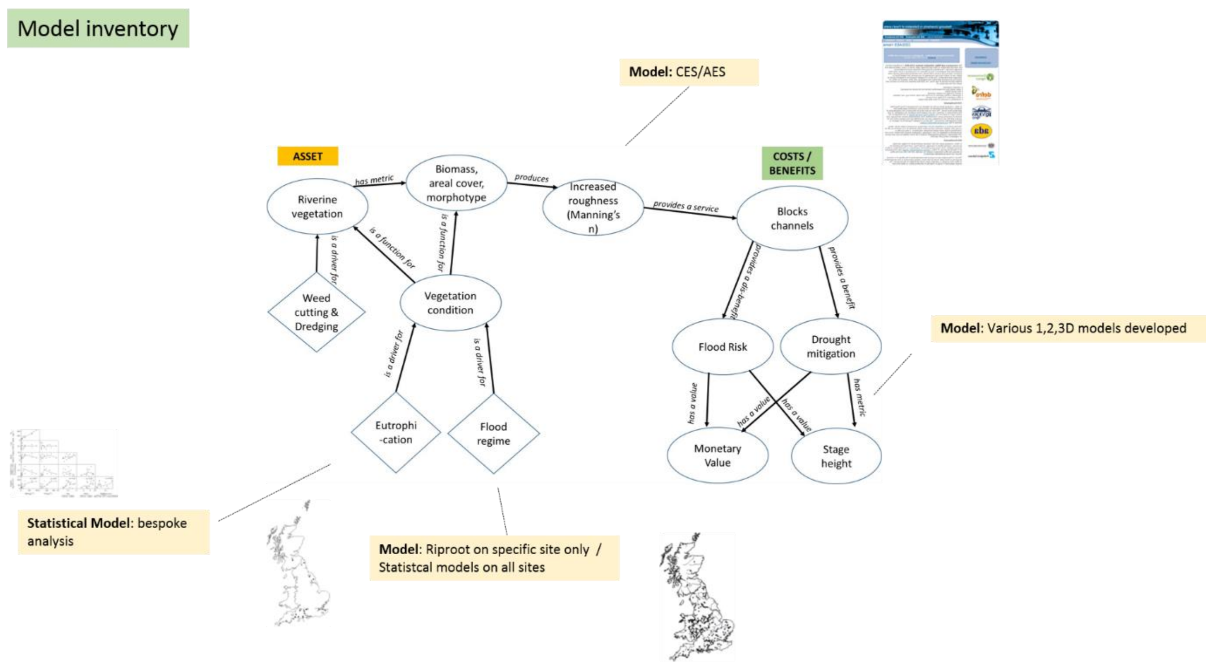


Figure 26: Models linked to flood risk and drought mitigation data graph

Modelling the impact of riparian trees on mitigating river flooding

Various models exist that, in combination, could provide a mechanism for predicting the potential role of trees in mitigating river flooding. These are shown in Figure 27. This approach has not yet been trialled on a UK scale.

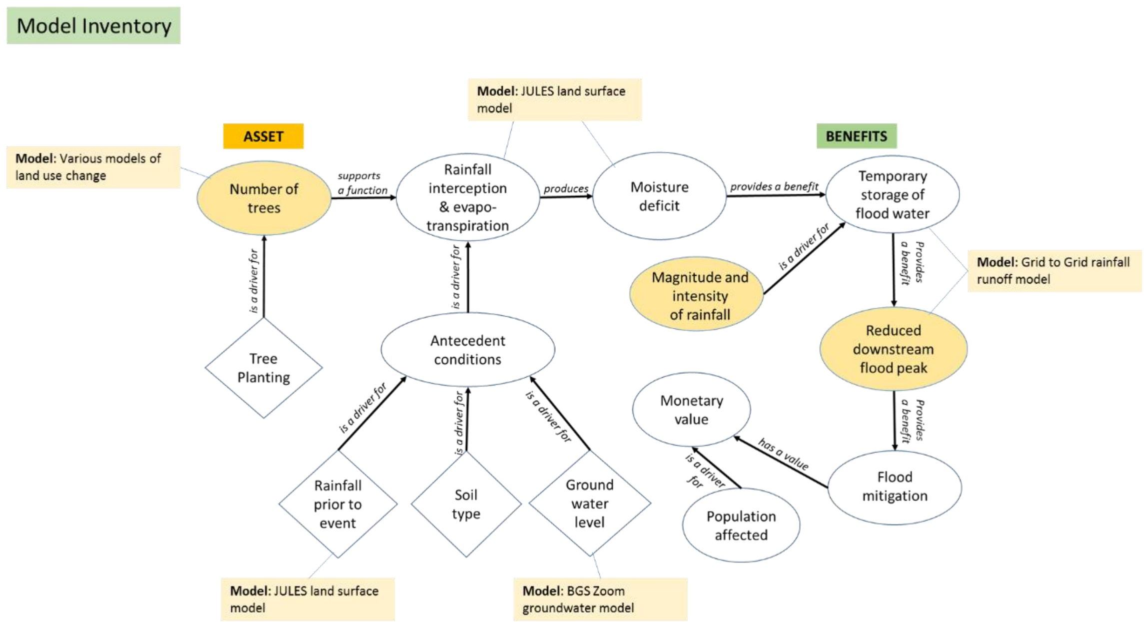


Figure 27: Models relating to the role of trees in regulating river flow data graph

Sea birds and renewable energy

Three types of models can be linked to the seabird and renewable energy evidence chain: collision risk models; displacement models; and integrated population models (Figure 28).

Collision risk models are used to assess the potential direct impacts of wind turbines on birds and usually involve calculating the probability of a collision occurring (assuming no avoidance behaviour) and estimating the likely number of collision events. A number of different models have been developed so far, however we are not aware of models operating at the national scale. A recent review of the literature is available in Masden & Cook (2016).

The displacement model was developed by CEH scientists for five seabird species and five SPAs in Scotland as part of a Scottish Government contract. A simulation model was developed that modelled the time/energy budgets of breeding seabirds during the chick-rearing period. Impacts of displacement on population size were considered to operate via reduced survival of offspring during the breeding season and via reduced body mass of adults leading to lower survival in the following winter. Simulated values of adult and chick survival were compared in models that included offshore wind farms against baseline simulations where no windfarms were present. Full details are available in Searle et al. (2014). The model was developed for parts of Scotland, however, with appropriate modifications it could be extended for use at UK scale.

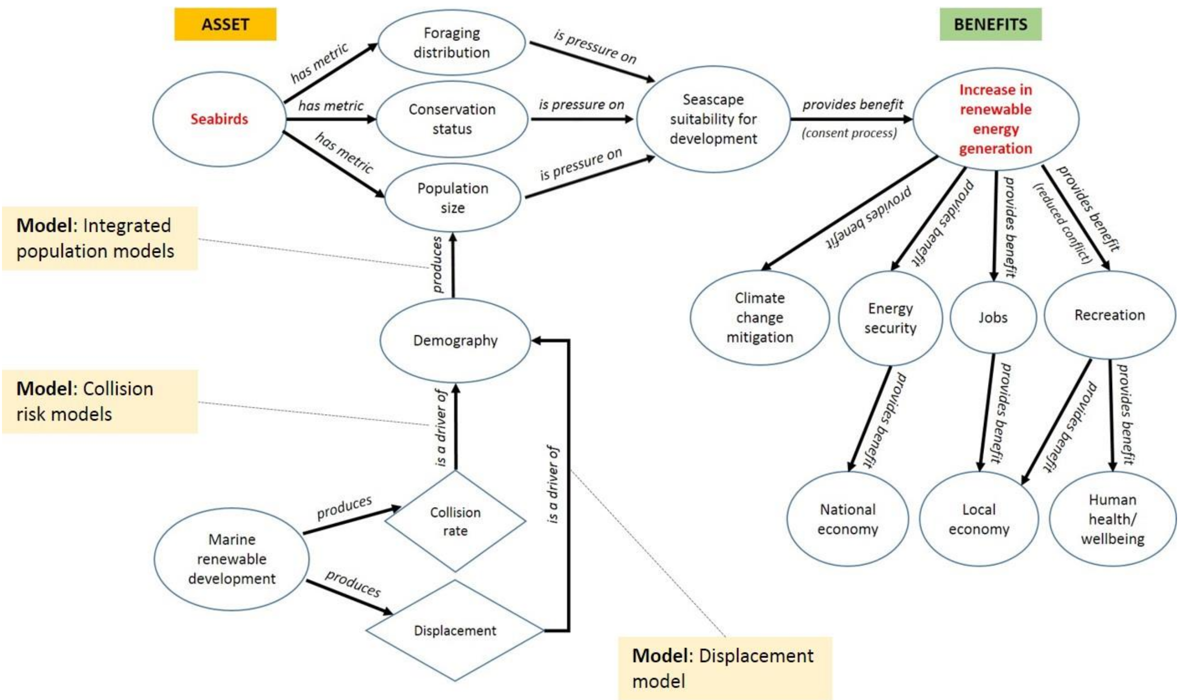


Figure 28: Models relating to the role of seabird conservation in the regulation of renewable energy sources data graph

Integrated population models (IPMs) for six seabird species and five SPAs in Scotland were previously developed by CEH scientists as part of a Scottish Government contract. Data on abundance, survival and breeding success were collated from a variety of sources. The models were fitted using a Bayesian approach, thus allowing for ‘observation error’ and environmental stochasticity simultaneously within the same model. The models were used to forecast population change 30 years into the future over the lifetime of proposed offshore wind farms, under different scenarios of decline in adult survival, breeding success or both caused by the developments. Full details are available in Freeman et al. (2014). The models were developed for parts of Scotland, however, with appropriate modifications they could potentially be used at UK scale.

5.5.2 Air case study – air quality regulation

The EMEP4UK atmospheric chemistry transport model has been linked to different parts of the evidence chain to create mapped outputs for ozone concentration, N deposition and $PM_{2.5}$ concentration as shown in Figure 29. This provides a consistent approach across the evidence chain.

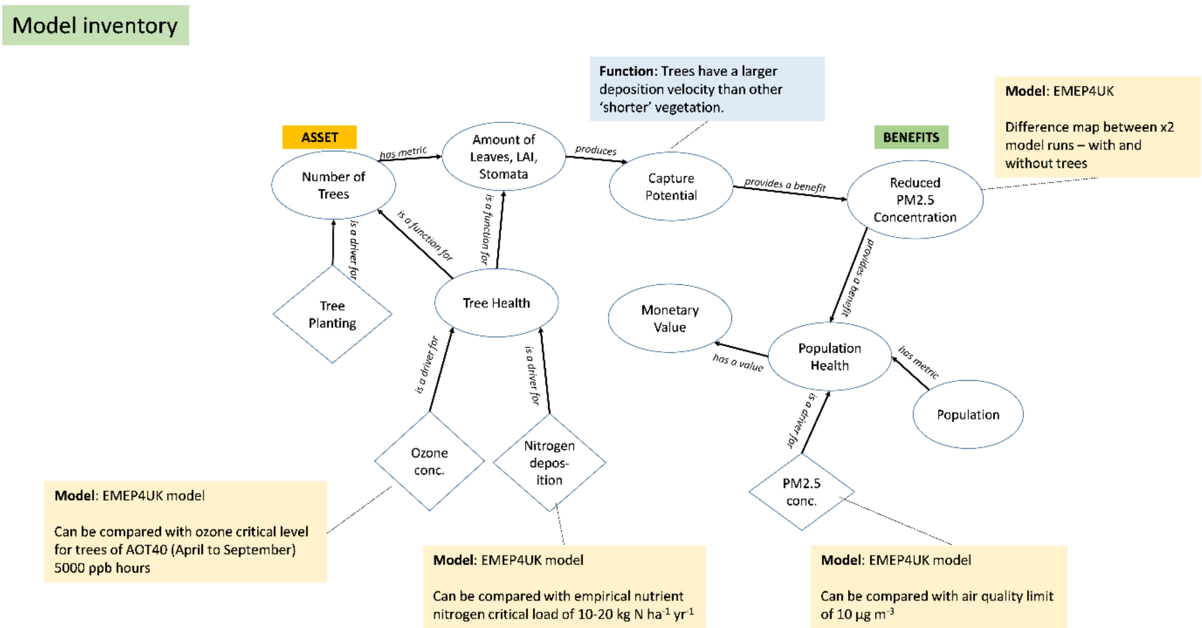


Figure 29: Models relating to the role of trees in regulating air quality data graph

6 National scale maps

Maps can be linked to the evidence chains representing primary datasets, derived datasets or model outputs. Some example maps from these different sources related to the land, water and air case studies are provided in this section.

6.1 Land case study – Pollination

National scale maps of individual pollinators are available on the NBN gateway (not shown here). A national scale map of nectar plant species for bumblebees and solitary bees has also been compiled through expert consultation and data analysis.

The Ecomaps approach has been used to provide a national natural capital metric for nectar producing plant species used by bees (see Figure 30(a)). The map uses data from 7408 CS plots (X, Y and U, 2*2m), within the 591 squares sampled in 2007. Generalised Additive Mixed Models (GAMMs) were fitted to plant species counts and matched with potential explanatory variables, recorded at either plot or 1km square level. A Poisson error structure with log link function was assumed and a random component (square) was included in the model to account for replicate plots within squares. Based on the fitted model a map of predicted species counts was produced over GB. Explanatory variables included altitude, broad habitat, air temperature, precipitation and nitrogen deposition (which negatively impacts on species richness). This map has been produced for 'England only' as one of a suite of maps[3] produced for Natural England.

[3] https://eip.ceh.ac.uk/naturalengland-ncmaps/reportsData

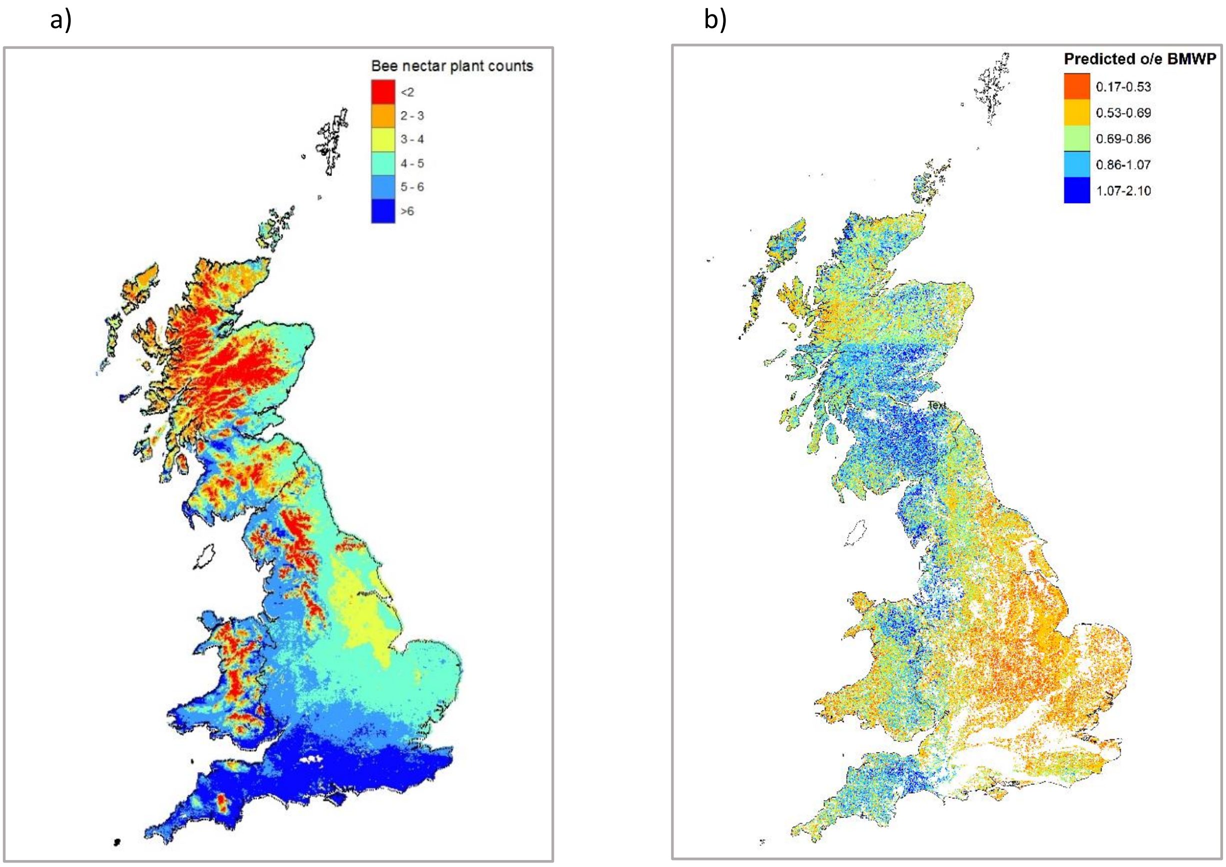


Figure 30: Maps produced using Ecomaps for Great Britain of: (a) bee nectar plant richness; and (b) headwater stream quality (predicted observed/expected biological monitoring working party score for aquatic invertebrates)

6.2 Water case studies

6.2.1 Headwater stream quality

The Ecomaps approach has been used to provide a national natural capital metric for headwater stream quality (see Figure 30(b) above). Using a method similar to that described for pollination, but in this case using a boosted regression tree approach, a model was fitted to predict the observed/expected biological monitoring working party (BMWP) score for aquatic invertebrates in headwater streams (Strahler order 1-3) across GB. The BMWP score is an index for measuring the biological quality of rivers using selected families of invertebrates as biological indicators (Armitage *et al.* 1983). A higher value on the map indicates that the water quality of headwater streams, as shown by the invertebrates, is better. The map was produced using observed/expected BWMP scores from headwater stream invertebrate samples, taken at 478 headwater stream sites across two survey years in the CS (1998 and 2007). From the invertebrates collected, observed BMWP scores were calculated for each sample site. Expected BMWP scores were calculated for "reference" invertebrate communities, based on the physical characteristics of the sampled sites. Predictions were extrapolated up to a national level on the basis of the boosted regression tree modelling using the predicted relationships between catchment characteristics (altitude, slope, stream order, woody cover along streams, and % land cover of arable, improved grassland or urban) and water quality for a randomly generated river sampling site in each unmonitored 1km square.

6.2.2 Lake water quality for drinking and recreation

Safe, clean water is critical for sustaining many of the essential ecosystem services that are provided by freshwaters, especially the supply of drinking water and recreational amenity. When cyanobacterial blooms develop in lakes and reservoirs, this affects the provision of these services.

The World Health Organisation (WHO) has set health alert thresholds for lakes in relation to the safe use of water for drinking and recreation. These are set in relation to the level of cyanobacteria in the lake water. However, the main pressure that causes this problem is nutrient enrichment. Much of the widespread increase in cyanobacterial blooms in recent decades has been attributed to this cause.

Carvalho et al. (2013), using data from over 800 European lakes, developed a simple model for relating risk of cyanobacterial blooms to the P concentration of the lake water. They found that cyanobacteria exhibited a non-linear response to P concentration, with the sharpest increase in cyanobacterial abundance occurring between about 20 µg P L^{-1} and about 100 µg P L^{-1}. In addition, the authors found that the likelihood of cyanobacteria exceeding the World Health Organisation (WHO) 'low health alert' threshold increases from about 5% at 16 µg P L^{-1} to 40% at 54 µg P L^{-1}. This relationship has been used to map the current suitability of lakes for drinking water and recreational use based on their likelihood of developing cyanobacterial blooms whose concentrations exceed WHO health thresholds in Water Framework Directive (WFD) lakes across England, Wales and Scotland (Figure 31).

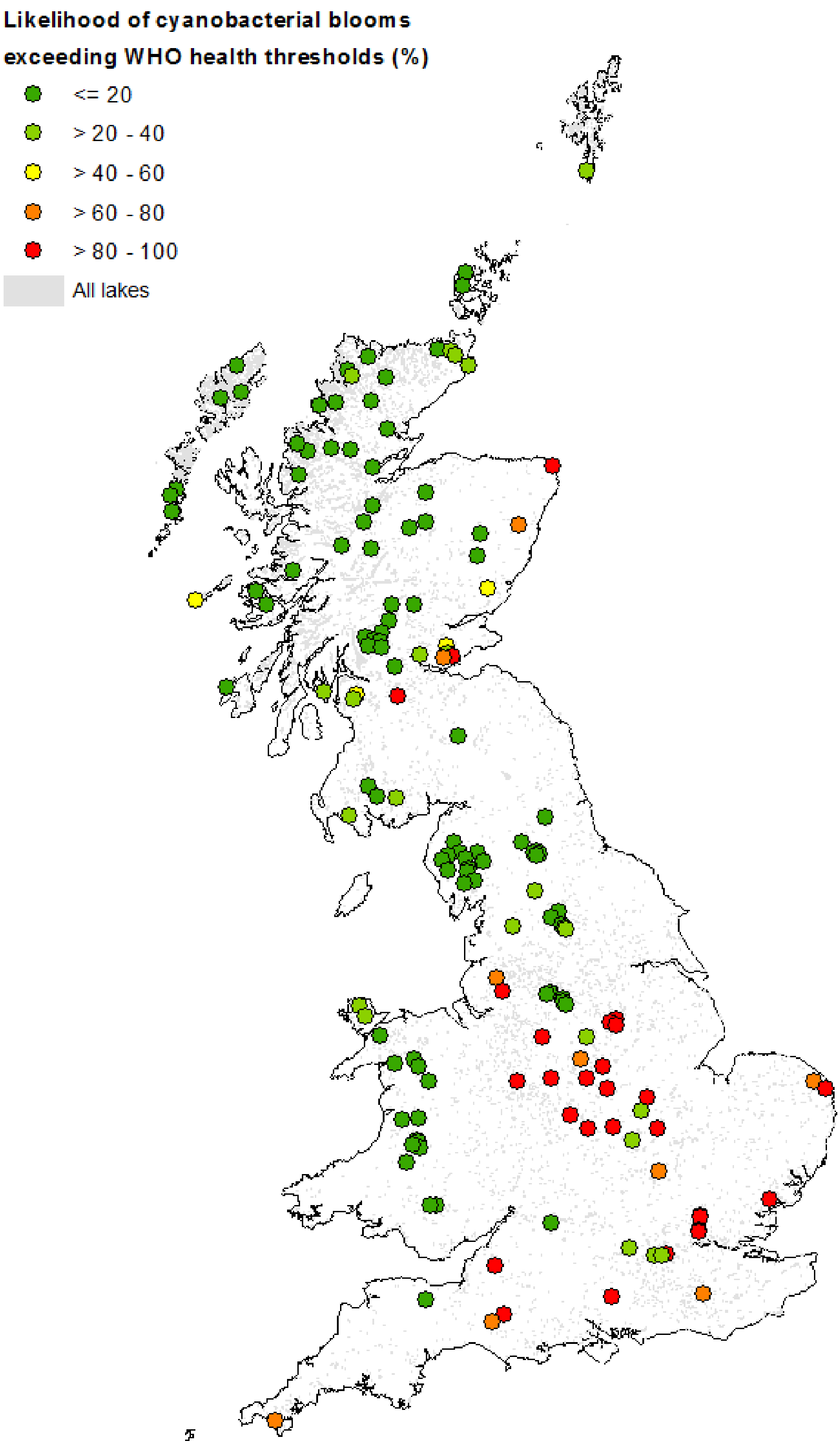


Figure 31: Suitability of Water Framework Directive (WFD) lakes for drinking water and recreational use in Great Britain. Map shows the modelled likelihood of cyanobacterial blooms exceeding World Health Organisation (WHO) health thresholds

6.3 Air case study – air quality regulation

The EMEP4UK atmospheric chemistry transport model (ACTM) was used to calculate the service provided by vegetation in removing air pollutants at a UK scale, for 2015. Using a fully dynamic modelling approach coupling meteorological drivers incorporates all the necessary pollutant dispersal mechanisms and interactions between air pollutants and meteorology, which govern the amount of service provided in reality. If these aspects are not accounted for, this can result in considerable over- or under-estimates of the service provided. The following example outputs illustrate the quantities of fine particle ($PM_{2.5}$) mass removed by vegetation over the UK, and the resulting change in $PM_{2.5}$ concentrations (i.e. the reduction in exposure to health-damaging pollutants) (Figure 32, next page).

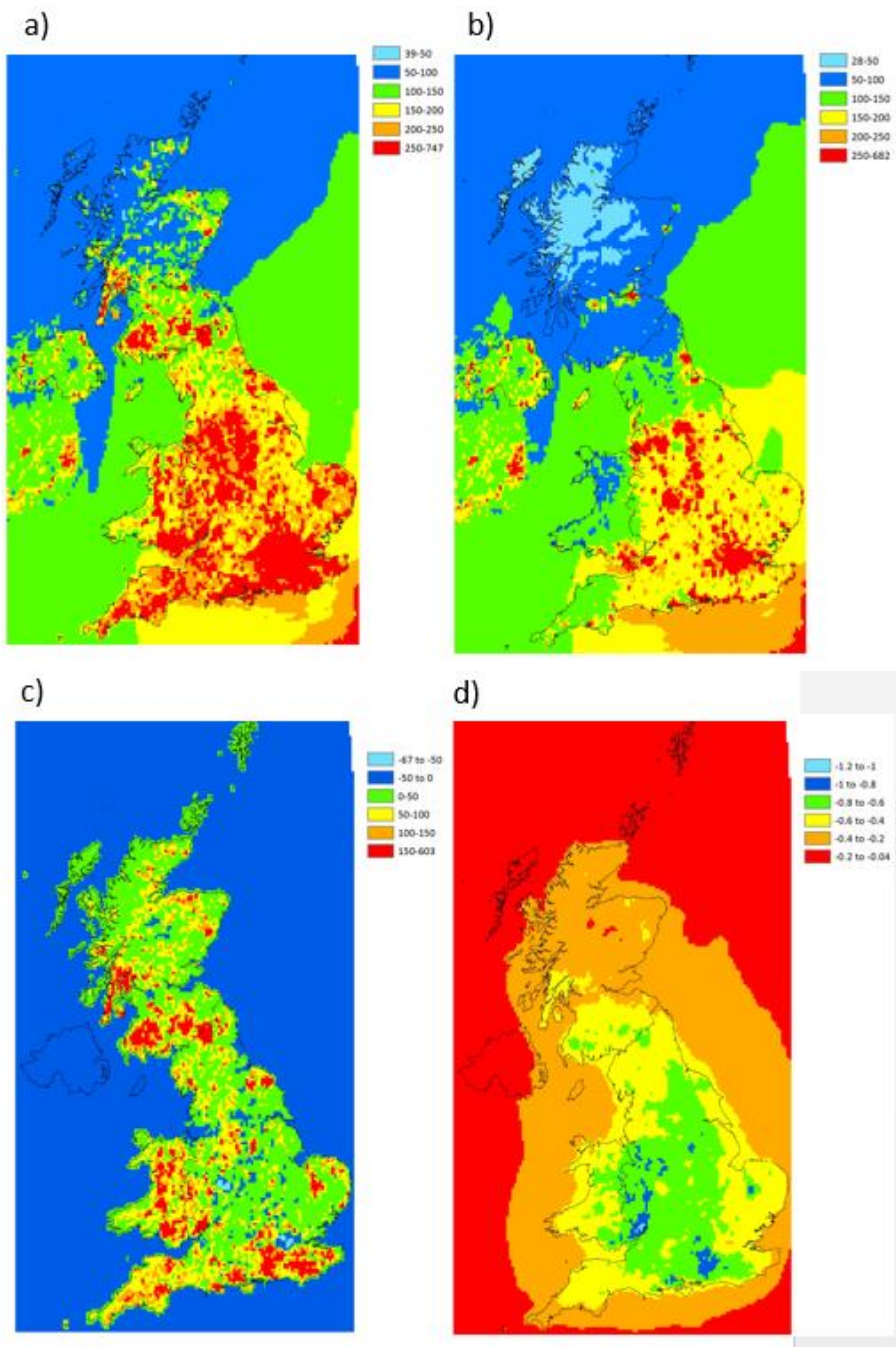


Figure 32: Maps of fine particulate matter ($PM_{2.5}$) removal by vegetation under two model scenarios using EMEP4UK, showing: (a) Pollutant removal with current UK vegetation; (b) Pollutant removal assuming no UK vegetation; (c) Difference map showing amount of pollutant removed by vegetation (red values show areas of greatest removal of $PM_{2.5}$ by vegetation); and (d) Resulting change in $PM_{2.5}$ concentrations (blue values show greatest reduction) (µg m^{-3})

7 Natural Capital Portal

One objective of the Natural Capital Metrics project is to develop an online portal providing access to datasets and project outputs, and to enable exploration of the chain of evidence linking natural capital to ecosystem services and human well-being. During Phase 1 of the project, considerable progress was made in scoping the requirements for such a portal and possible technical solutions. In Phase 2 we anticipate launching a first version of the portal.

Achievements in Phase 1 included:

- Identifying groups of potential stakeholders/users
- Identifying a set of user stories useful in identifying required software features
- Exploring possible technical solutions, particularly to enable visual presentation of natural capital evidence chains ('data graphs'; see example in Figure 33)
- Demonstrating that the database is able to reveal connections between evidence chains that contain related concepts. For example, the pollinators and air quality chains both contain the concept of "Nitrogen deposition" and the software can visualise the links between them (Figure 33).

The following portal components were agreed as necessary:

- A metadata catalogue describing datasets and models related to natural capital. The catalogue will allow searches to be constructed through either the dataset or model and will display linkages between them
- A map viewer to view relevant spatial data
- An RDF triple store[4] that will act as the database to store evidence chains
- A graph visualisation tool to enable the exploration of evidence chains and to allow users to navigate between different entry points
- A controlled vocabulary of natural capital terms (glossary)
- A web framework to develop the portal/knowledge hub.

[4] An RDF triple store is a database that stores data in Resource Description Framework (RDF) format. It's a data modelling concept based upon the idea of making statements about resources in the form of **subject–predicate–object** expressions, known as triples. The subject denotes the resource, the predicate denotes traits or aspects of the resource, and expresses a relationship between the subject and the object (https://en.wikipedia.org/wiki/Resource_Description_Framework).

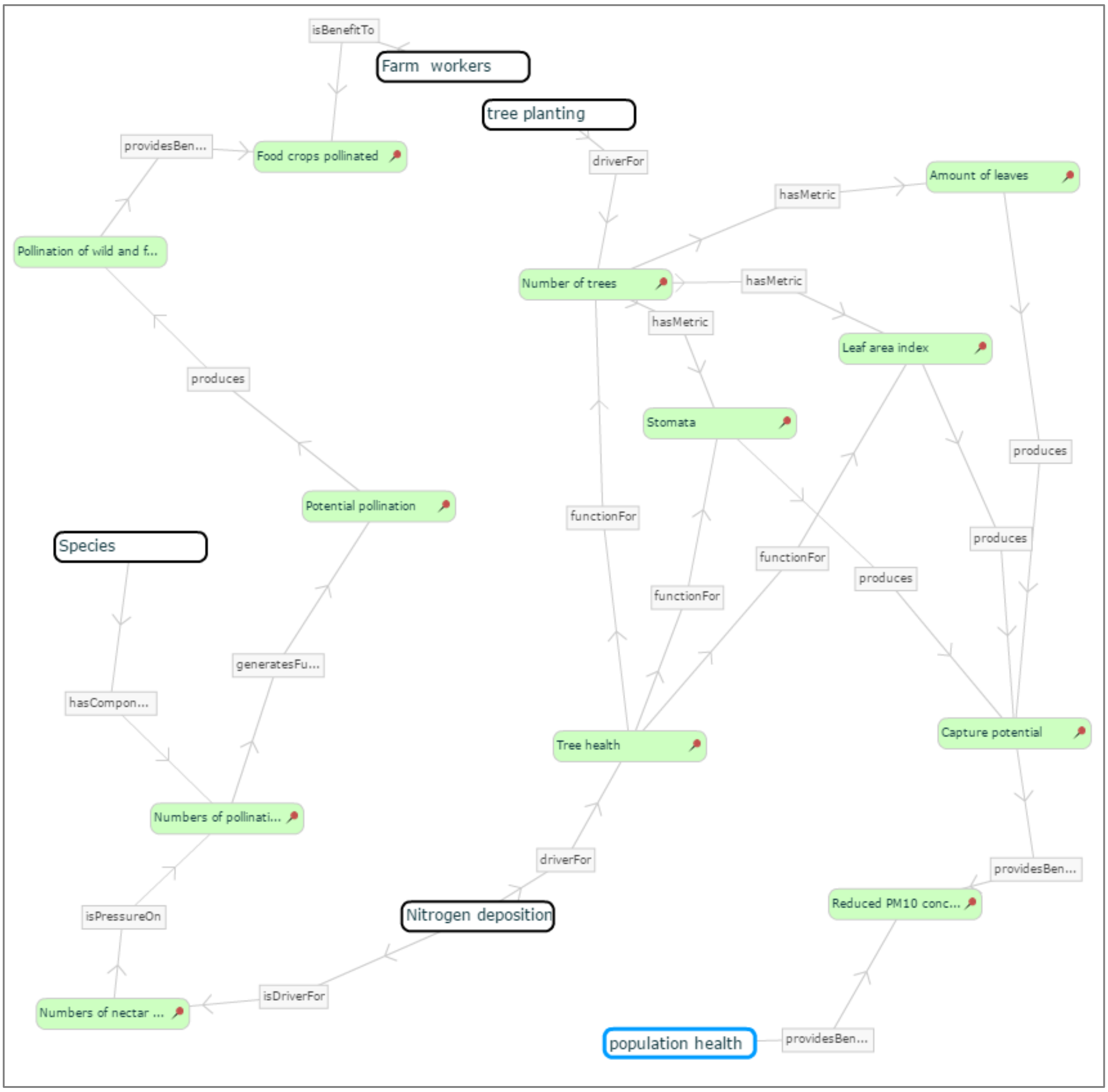


Figure 33: Two data graphs linked by a common node (nitrogen deposition)

The next steps in portal development (to be undertaken in Phase 2 of the project) include:

- More rigorously testing the ontology and approach against a larger number of example evidence chains;
- Defining the tools required to query, visualise and link out to relevant concepts based on the final agreed conceptual framework and associated evidence chains;
- Identifying and testing these tools with the user community;
- Identifying the datasets, models, systematic reviews, etc. required to populate the portal, building on the data inventories and the model catalogue described earlier;
- Creating a natural capital portal/knowledge hub.

8 Conclusions and next steps

Humans are dependent on goods and services provided by the natural environment, including assets such as soils, trees, water, air and species. This natural capital underpins the benefits that the natural environment contributes to people, but at the same time human development has caused significant losses in biodiversity through overexploitation and other drivers of change. The NCMet project has developed an overall conceptual framework illustrating the linkages between drivers and pressures of environmental change, how they affect interactions between natural capital assets and human beneficiaries within socio-ecological systems to determine the delivery of ecosystem services, and policy and management responses to mitigate detrimental impacts from pressures or manage potential synergies and trade-offs between ecosystem services.

Work in this first phase of the NCMet project has focused on collating evidence to better understand the mechanisms and science underlying the links between natural capital assets and human benefits focusing on case studies in land, water and air systems. Six case studies have been explored:

- Pollination for the provision of food;
- Lake water quality regulation;
- Flood mitigation through tree planting;
- Flood risk and drought mitigation through riverine vegetation;
- The role of sea birds in the regulation of renewable energy sources;
- Air quality regulation for human health.

For each case study an evidence chain was constructed showing the interrelationships between pressures, natural capital assets and human benefits. The evidence, datasets and models related to these evidence chains was also documented. The process of producing the evidence chains proved to be highly complex and varied substantially across the different case studies. It was particularly difficult to depict the evidence chains in a clear and transparent, yet consistent, manner across the different case studies whilst not over-simplifying underlying relationships or processes. Furthermore, care had to be taken to ensure parts of the evidence chains were not omitted due to lack of evidence or bias in the literature supporting certain relationships but not others. This led to the development of a highly flexible ontology that worked well in this first exploratory stage of the project. The challenge now is to consolidate the lessons learnt throughout this process and refine the ontology into a workable data model that can be used to make the findings of the project available through a natural capital portal or knowledge hub.

This will be the main focus of the next stage of the project. It will involve the further refinement of the existing evidence chains, dataset and models for incorporation into the portal, and the development of new evidence chains to further test and refine the ontology and portal design. Additionally, drivers and pressures of relevance to the evidence chains will be identified and evidence compiled of how such drivers influence the natural assets, their interdependencies, and the resulting benefits to human well-being. We will particularly focus on climate, land use and pollution drivers (linked to other drivers as necessary) in order to complement future long-term work plans. User feedback on the portal design will be sought to inform this process and ensure that natural capital metrics and sources of evidence at each point in the evidence chains from datasets, literature reviews and models are clearly depicted to provide a transparent audit trail. This will advance understanding of interdependencies between human and environmental systems that are key to managing the natural environment and the pressures that affect it.

8.1 Links to other CEH projects

This work has strong links with CEH monitoring across all areas (land, water and air) and with NC projects supporting that monitoring. Some of our monitoring is relatively straightforward to integrate – in particular where monitoring has been designed to be nationally representative. LCM and CS were co-developed in order to enable just such integration of approaches – where a coarse national EO dataset can be combined with highly resolved nationally representative sampling to enable extrapolation of findings (as has been done in EcoMaps). CS also combines monitoring of water, soil and land within it and this enables much better understanding of the co-dependencies and interactions between the ecosystem components in the production of services. This is evidenced by the headwater stream quality map (Section 0, Figure 30(b)). Other aspects of CEH monitoring are less straightforward to integrate, but have proved highly valuable in validation and/or in allowing us to explore other aspects of the natural capital variables that we measure. For example, the Environmental Change Network (ECN) data allows us to understand how more highly resolved temporal variability in vegetation relates to the variability we see over decadal surveys.

9 Annex 1: Relevant datasets

Work has begun on compiling a list of relevant datasets held by CEH. This will be taken further in phase 2 of the project, aiming towards a master list of relevant land, water and air datasets. The principal land-related datasets cover ecological communities, species and soil, and the main sources are Countryside Survey, Land Cover Map, the National Biodiversity Network and the Environmental Change Network. The major water-related datasets cover data on external drivers and pressures, catchments, lakes, rivers, and wetlands. In addition to CEH datasets, a list of water-related third party datasets has been compiled. Finally, for air, datasets comprise both model input data and model outputs of meteorological drivers, as well as atmospheric constituents for present day conditions, and scenarios. The model outputs are complemented by key atmospheric observations from a range of UK monitoring networks.

10 Annex 2: Glossary of terms

Glossary of terms (rows ☐, signify terms used in association with the evidence chains)

Term	Definition
Asset	Something of value.
Attribution	The process of identifying variables which have a causal effect on a given parameter.
Benefit	An advantage, good effect.
Beneficiary	A person or group who receives benefits.
Biodiversity	The variability among living organisms from all sources including terrestrial and freshwater ecosystems and the ecological complexes of which they are part; this includes diversity within and among species and diversity within and among ecosystems.
Broad and Priority Habitats	A classification of UK habitats produced for UK Biodiversity Action Plan reporting.
Conceptual framework	A way of organising ideas in order to make them easily accessible.
Condition (relating to stocks of natural capital)	The capacity of a ‘stock’ to yield ecosystem services relative to its potential capacity.
Cultural capital	Values, beliefs and socially held knowledge that allow us to interact with one another and our environment.
Cultural services	The nonmaterial benefits that people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation and aesthetic experience, including, for example, knowledge systems, social relations, and aesthetic values.
Data resource	Data that is available to an organisation or through a data catalogue

Term	Definition
Driver	The underlying causes of change in an ecosystem which may be human induced or natural, but are exogenous (external) to the ecosystem.
Ecosystem	A dynamic complex of plant, animal and micro-organism communities and their non-living environment interacting as a functional unit.
Ecosystem benefits	A benefit is something that has an explicit impact on changes in human welfare, e.g. improved walking conditions or decreased flooding.
Ecosystem function	An intrinsic ecosystem characteristic related to the set of conditions and processes whereby an ecosystem maintains its integrity (such as primary productivity, food chain, biogeochemical cycles). Ecosystem functions include such processes as decomposition, production, nutrient cycling and fluxes of nutrients and energy.
Ecosystem properties	Emergent properties of an ecosystem that represent more than the sum of its individual components, e.g. resilience.
Ecosystem services	Benefits that humans recognise as obtained from ecosystems that support, directly or indirectly, their survival or quality of life. These include a range of intermediate services which may be involved in **regulation** (e.g. flood control), **support** (e.g. nutrient cycling) or **provisioning** (e.g. pollination) of ecosystems. These services are essential for maintaining conditions for life on earth. **Ecosystem disservices** are ecosystem functions that are harmful to humans.
Ecosystem processes	The interactions among biotic and abiotic elements of ecosystems which underlie an ecosystem function.
Entity	Something that exists apart from other things.
Final services	These services derive from a range of intermediate services and result in a direct benefit to humans e.g. provision of clean water.
Flow	The term flow relates to the services and benefits arising from natural capital assets.
Financial capital	Has no intrinsic value but enables other forms of capital to be owned or traded.
Function	An activity that is natural or to the purpose of.
Habitat	Area occupied and supporting living organisms. Also used to mean the environmental attributes required by a particular species or its ecological niche.
Human capital	Individuals' skills, knowledge, abilities, social attributes, personality and health attributes.

Term	Definition
Interactions including trade-offs	In all ecosystems interactions between different ecosystem services may occur. In some cases different services may be positively related with one another, and in others the reverse may occur, e.g. a decrease in the nutrient cycling capacity of soil as a result of its use for food production under particular agricultural systems. The latter situation may be referred to as a trade-off between services.
Intermediate services	Intermediate ecosystem services provide inputs to the biophysical production of final services. They are not valued directly by people. Examples are water purification or nutrient cycling.
Land use	The human utilisation of a piece of land for a certain purpose (such as agriculture or recreation).
Landscape	An area of land that contains a mosaic of ecosystems, including human-dominated ecosystems. The term *cultural landscape* is often used when referring to landscapes containing significant human populations.
Metric	A standard of measurement.
Model	Mathematical approaches which attempt to describe real world relationships between a range of parameters in order to further understanding of ecosystems and enable prediction of future conditions under different scenarios.
Natural Capital	The stock of natural assets which include geology, soil, air, water and all living things. It is from this Natural capital that humans derive a wide range of services, often called ecosystem services, which make human life possible.
Ontology	A set of concepts and categories in a subject areas or domain that shows their properties and the relations between them.
Pollination	The completion of the sexual phase of reproduction in some plants by the transfer of pollen. In the context of ecosystem services, pollination generally refers to animal-assisted pollination, such as that done by bees, rather than wind pollination.
Potential ecosystem service	The service provided by an ecosystem irrespective of whether it is used by humans.
Pressure	The endogenous (or internal) variables that quantify the effect of drivers within an ecosystem.
Produced capital	Material goods and infrastructure that contribute to the production of goods.

Term	Definition
Provisioning services	The products obtained from ecosystems, including, for example, genetic resources, food and fibre and fresh water. The end products may be seen as ecosystem benefits.
Realised ecosystem service	The service provided by an ecosystem that is actually used by humans
Regulating services	Intermediate services which involve the regulation of ecosystem processes, including, for example, the regulation of climate, water, and some human diseases.
Relationship	The ways in which entities are related to one another.
Resilience	The capacity of a system to tolerate impacts of drivers without irreversible change in its outputs or structure.
Responses	Action through policy and management aiming to minimise negative impacts (or maximise positive impacts) on ecosystems by acting on the pressure or state variables associated with natural capital assets and beneficiaries.
Social capital	The social structures, institutions, networks and relationships than enable individuals.
Socio-ecological system	A system that includes societal (human) and ecological (biophysical) subsystems in mutual interactions (Gallopin 1991) and thus captures interactions between ecosystems, biodiversity and people (Harrington et al., 2010).
Stock (natural assets/resources)	The amount of the natural assets (biotic/abiotic) which make up natural capital.
Structure	The spatial and/or temporal configuration of an ecosystem.
Supporting services	Intermediate ecosystem services that are necessary for the production of all other ecosystem services. Some examples include biomass production, production of atmospheric oxygen, soil formation and retention, nutrient cycling, water cycling and provisioning of habitat.
Taxa	Nested groups of species that reflect similarity. Familiar taxa are birds (which belong to the class *Aves*).
Upscaling	The process of aggregating or extrapolating information collected at a fine resolution to a courser resolution or greater extent.

Term	Definition
Value	The importance, worth or usefulness of an object or action

11 Annex 3: Model/tool catalogue

Selected fields from model catalogue. Application scale: 1) Plot, 2) Field, 3) Farm, 4) River reach, 5) Catchment, 6) Landscape, 7) Regional, 8) National, 9) International. Natural capital/Ecosystem service codes: 1) Natural capital stocks; 2) Natural capital stocks & processes; 3) Ecosystem services potential; 4) Ecosystem services realised; 5) Benefit; 6) Trade-offs.

Model name	Primary purpose	Application scale	Natural Capital	Natural Capital / ES (coded)	Natural Capital Components	Ecosystem Services & biodiversity
1D-ICZ	Predicts effects of management on soil organic matter, aggregation, hydrology and water release.	1,2	Natural Capital - processes & stocks; Ecosystem Service - potential	2,3	soil attributes, soil carbon, water supply	water supply
BASECO	BASECO is a simplified version of BASFOR but is able to simulate grasslands, crops and heathlands as well as forests	1,2	Natural Capital - processes & stocks; Ecosystem Service - potential	2,3	wood yield; grass yield	wood production; grass production
BASFOR	BASFOR is a BASic FORest model, with simple representation of forest biogeochemistry. BASFOR simulates soil-plant-atmosphere processes of deciduous and coniferous forest stands. Interactions with the atmospheric and soil environment are simulated in some detail, as are the impacts of management: thinning and pruning. Three biogeochemical cycles are simulated: carbon, nitrogen and water. BASFOR is a one-dimensional model, so no horizontal heterogeneity of the forest is captured. BASFOR does not simulate wood quality or pests and diseases.	1,2	Natural Capital - processes & stocks; Ecosystem Service - potential	2,3	wood yield	wood production

Model name	Primary purpose	Application scale	Natural Capital	Natural Capital / ES (coded)	Natural Capital Components	Ecosystem Services & biodiversity
BASGRA	The grassland model BASGRA is a mechanistic model for simulating the year-round dynamics of tillers, leaves, roots and reserves. The model simulates the response of the sward to soil conditions, cutting, day length, and the weather including winter stresses. The model operates at a daily time step and contains 23 state variables and 71 initial constants and other parameters.	1,2	Natural Capital - processes & stocks; Ecosystem Service - potential	2,3	grass yield	grass production
Bayesian occupancy modelling	Predicts occupancy probability for species in the presence of imperfect detectability. Can be extended in any number of ways, as is simply an implementation of Bayesian statistics.	7,8	Natural Capital - stocks only; Ecosystem service - potential	1,3	species composition	biodiversity
CAF2007	CAF2007 is a simple dynamic model of coffee agroforestry systems. The model includes the physiology of vegetative and reproductive growth of coffee plants, and its response to different growing conditions. This is integrated into a plot-scale model of coffee and shade tree growth which includes competition for light, water and nutrients and allows for management treatments such as spacing, thinning, pruning and fertilising. The model can be used to examine tradeoffs between increasing coffee and tree productivity, and between maximising productivity and limiting the impact of the system on the environment: greenhouse gas emissions (N2O, NO, CO2), N-leaching, erosion.	1,2	Natural Capital - processes & stocks; Ecosystem Service - potential; Ecosystem Service - realised	2,3,4	coffee yield;	coffee production;

Model name	Primary purpose	Application scale	Natural Capital	Natural Capital / ES (coded)	Natural Capital Components	Ecosystem Services & biodiversity
CASCADE	Dynamically simulates movement of water, solutes and suspended material through catchments with in-stream processes	4,5	Natural Capital - processes & stocks; Ecosystem Service - potential	2,3	water supply, water quality	water supply, nutrient regulation
CLIMSAVE IAP/IAP2	Modelling of future cross-sectoral impacts, adaptation and vulnerability in the context combined climatic and socio-economic change	8,9 (Scotland and Europe)	Natural Capital - processes & stocks; Ecosystem Service - potential; Trade-offs	2,3,6	land use naturalness, land use diversity, biodiversity	food, water supply, timber, carbon sequestration, biodiversity
ECOMAPS	A statistical approach which provides national natural capital metrics. Models are spatially explicit and use high resolution sampled data in combination with national datasets and LCM to extrapolate measures.	2,3,4,5,6,7,8	Natural Capital -stocks only; Ecosystem Service - potential	1, (3)	soil carbon	carbon stock
EMEP4UK	The EMEP4UK rv4.10 is an open source off-line atmospheric-chemistry transport model (ACTM) based on the EMEP MSC-W model. The model, termed EMEP4UK, is capable of representing UK atmospheric composition in greater detail, with the ability to simulate hourly air pollution interactions over decadal time scales using a 5km grid or finer.	2,3,5,6,7,8 (input data from 1-2 upwards; outputs at resolution of 4 upwards)	Natural Capital - processes & stocks; Ecosystem Service - potential; Ecosystem Service - realised	2,3,4	air quality	air quality regulation, (local temperature regulation)

Model name	Primary purpose	Application scale	Natural Capital	Natural Capital / ES (coded)	Natural Capital Components	Ecosystem Services & biodiversity
ESTIMAP (recreation)	Mapping of ecosystem service provision (recreation use), potential and uptake. There are also modules on pollination and air quality.	1,2,3,4,5,6,7	Natural Capital - processes & stocks; Ecosystem Service - potential; Ecosystem Service -realised; Benefit; Trade-offs	2,3,4,5,6		Recreation
FRAME	Calculates deposition of sulphur and nitrogen and heavy metals as well as gas and aerosol concentrations across the UK	5,6,7,8 National scale coverage with 1 km or 5 km options for grid resolution	Natural Capital - processes & stocks; Ecosystem Service - potential	2,3	air quality	air quality regulation
FRESCALO	Predicts relative occurrence probability of taxa recorded opportunistically. Adjusts for biases related to recording effort (although not recording focus).	7,8	Natural Capital - stocks only; Ecosystem service - potential	1,3	species composition	biodiversity

Model name	Primary purpose	Application scale	Natural Capital	Natural Capital / ES (coded)	Natural Capital Components	Ecosystem Services & biodiversity
InVEST	Suite of 18 open-source ecosystem services models, including cultural services. Models are spatially explicit and can map and value (in economic or biophysical terms) ecosystem service provision.	2,3,4,5,6,7,8 (scale of outputs varies with model, e.g. water yield model outputs are at catchment scale.	Natural Capital - processes & stocks; Ecosystem Service - potential; Ecosystem Service - realised	2,3,4	soil carbon, above-ground carbon, water quality, landscape attributes	agricultural productivity, water supply, nutrient regulation, sediment regulation, carbon stock, pollination, recreation, +MORE
LTLS-IM	Predicts effects of pollution, climate change and land management on soil organic matter and water quality.	5,6,7,8	Natural Capital - processes & stocks; (Ecosystem Service - potential)	2,3	soil carbon, water quality	nutrient regulation
LUCI	Simulates current condition and potential to improve ecosystem services. Outputs for agricultural productivity, habitat connectivity, carbon storage in soils and biomass, mitigation of flood risk and diffuse pollution, and trade-offs between these services.	1,2,3,4,5,6,7, 8	Natural Capital - processes & stocks; Ecosystem Service - potential; Trade-offs	2,3,6	soil carbon, above-ground carbon, water quality	agricultural productivity, habitat connectivity, carbon stock, flood mitigation, nutrient regulation

Model name	Primary purpose	Application scale	Natural Capital	Natural Capital / ES (coded)	Natural Capital Components	Ecosystem Services & biodiversity
LULUCF Local Authority emissions mapping	To map LULUCF emissions by local authority area by disaggregating national LULUCF data. Emissions are mapped by for LULUCF land use categories and for the main activities within these categories. With some development it would be possible to use a similar approach to map LULUCF emissions to other regional polygons.	6,7,8	Natural Capital - processes & stocks; Ecosystem Service - potential; Ecosystem Service - realised	2,3,4	GHG emissions	climate regulation
MADOC	Predicts effects of atmospheric N and S pollution on soil carbon, soil pH, and leaching e.g. of nitrate and dissolved organic matter.	1,2,5,8	Natural Capital - processes & stocks	2	soil attributes, soil carbon	
MADOC-MultiMOVE	Predicts effects of atmospheric N and S pollution on habitat-suitability for UK plant and lichen species and on 'overall habitat quality'.	1,2,5,8	Natural Capital -stocks only	1	species composition - plants	biodiversity
MAGIC	(MAGIC) Model of Acidification of Groundwater in Catchments. Simulates effects of acidic deposition on soils and surface waters. Includes all major ions and does complete acid-base chemistry ion soils and water, including exchangeable base cations in soils).	1,2,3,4,5,6,7,8	Natural Capital - processes & stocks; Ecosystem Service - potential	2,3	water supply, water quality	water supply, nutrient regulation
MultiMOVE	Predicts effects of changes in trait-means representing climate, fertility, alkalinity, etc. on habitat-suitability for ~1300 UK plant and lichen species.	1,8	Natural Capital -stocks only	1	species composition - plants	biodiversity

Model name	Primary purpose	Application scale	Natural Capital	Natural Capital / ES (coded)	Natural Capital Components	Ecosystem Services & biodiversity
N14CP	Predicts effects of atmospheric N pollution, climate change and land management on soil carbon, N and P availability, and leaching e.g. of nitrate and dissolved organic matter.	1,2,5,8	Natural Capital - processes & stocks	2	soil attributes, soil carbon, soil nutrients	
OECD lake models	Suit of simple models that predict in-lake nutrient and chlorophyll a concentrations from nutrient inputs and flushing rate.	5,6	Natural Capital - processes & stocks; Ecosystem Service - potential	2,3	water quality	nutrient regulation
PCLake	PCLake model - simulates responses across trophic levels from plankton to fish and waterfowl in lakes. Designed to predict responses in time and includes hysteresis based on feedback mechanisms operating in lakes. Only model that allows assessment of resilience in this way. Allows responses to multiple and interacting stressors including nutrients, fish manipulation, extreme rain, wind, temperatures etc.	5,6 (Landscape, Lake)	Natural Capital - processes & stocks; Ecosystem Service - potential	2,3	water quality	nutrient regulation
Photoseries	Using flicr other social-media photographs to map realised cultural ecosystem service uptake	1,2,3,4,5,6,7	Ecosystem Service - realised	4		Recreation
PROSUM	Predicts effects of nutrient availability, climate and vegetation management on biomass stocks and organic matter fluxes of C, N, P, K, Mg & Ca.	1,2	Natural Capital - processes & stocks	2	above-ground carbon	

Model name	Primary purpose	Application scale	Natural Capital	Natural Capital / ES (coded)	Natural Capital Components	Ecosystem Services & biodiversity
PROTECH	Water quality model which predicts the growth of phytoplankton in lakes and reservoirs, particularly cyanobacteria.	4	Natural Capital - processes & stocks	2	phytoplankton	biodiversity
QUESTOR	(QUESTOR) Quality Evaluation and Simulation Tool for River Systems. Simulate water quality in rivers especially eutrophication for scenario analysis. QUESTOR represents a river as a series of river reaches within which physical, chemical and biological processes operate.	4,5	Natural Capital - processes & stocks; Ecosystem Service - potential	2,3	water supply, water quality	water supply, nutrient regulation
Quickscan	Scenarios tool using rule-based application. Working with stakeholder groups to discuss future options for land management, rapid application of rules to spatial data to explore scenarios	1,2,3,4,5,6,7,8,9	Natural Capital - processes & stocks; Ecosystem Service - potential; Ecosystem Service -realised; Benefit; Trade-offs	2,3,4,5,6	Many possibilities	Many possibilities

Model name	Primary purpose	Application scale	Natural Capital	Natural Capital / ES (coded)	Natural Capital Components	Ecosystem Services & biodiversity
RIVPACS	(RIVPACS) River Invertebrate Prediction and Classification System. IVPACS offers site-specific predictions of the macro-invertebrate fauna to be expected in UK river sites in the absence of major environmental stress. An expected fauna is derived from RIVPACS using environmental predictor variables.	4,5	Natural Capital -stocks only	1	species composition - aquatic macro-invertebrates	biodiversity
Sparta	R package combining several models, including Frescalo, Bayesian occupancy models, mixed models etc. for analysing species occurrence data	7,8	Natural Capital - stocks only; Ecosystem service - potential	1,3	species composition	biodiversity
RANDOM FOREST - TOOLS	A statistical approach which provides national natural capital metrics. Models are spatially explicit and use high resolution sampled data in combination with national datasets and LCM to extrapolate measures.	2,3,4,5,6,7,8	Natural Capital -stocks only; Ecosystem Service - potential	1, (3)		
BOOSTED REGRESSION TREE - TOOLS	A statistical approach which provides national natural capital metrics. Models are spatially explicit and use high resolution sampled data in combination with national datasets and LCM to extrapolate measures.	2,3,4,5,6,7,8	Natural Capital -stocks only; Ecosystem Service - potential	1, (3)		

12 Annex 4: References & links

12.1 Publications

Aber, J.D., Nadelhoffer K.J., Steudler P., Melillo J.M. (1989). Nitrogen saturation in northern forest ecosystems. BioScience 39, 378-386

Armitage, P.D., Moss, D., Wright, J.F., Furse, M.T., 1983. The performance of a new biological water quality score system based on macroinvertebrates over a wide range of unpolluted running-water sites. Water Res. 17, 333–347.

Bealey, W. J., et a; (2007). Estimating the reduction of urban PM10 concentrations by trees within an environmental information system for planners. Journal of Environmental Management, 85, 44-58.

Beckett, K. P., Freer-Smith, P. H., and Taylor, G. (1998) Urban woodlands: their role in reducing the effects of particulate pollution. Environmental Pollution 99, 347–360.

Beckett KP, Freer Smith PH, Taylor G (2000a) Effective tree species for local air quality management. Journal of Arboriculture 26:12–19.

Beckett, K. P., Freer-Smith, P. H., and Taylor, G. (2000b) Particulate pollution capture by urban trees: effect of species and windspeed. Global Change Biology 6 (8), 995–1003.

Berkes F, Folke C (eds) (1998) Linking social ecological systems: Management Practices and Social Mechanisms for Building Resilience. Cambridge University Press, Cambridge, UK

Bobbink R. & Hettelingh JP (2011) Effects of nitrogen deposition on woodland, forest and other wooded land (EUNIS class G). In: Review and revision of empirical critical loads and dose-response relationships. RIVM Report 680359002, pp 135 – 171

Boerema, A., Rebelo, A.J., Bodi, M.B., Esler, K.J. and Meire, P. (2016). Are ecosystem services adequately quantified? Journal of Applied Ecology.

Carvalho, L., McDonald, C., de Hoyos, C., Mischke, U., Phillips, G., Borics, G., Poikane, S., Skjelbred, B., Lyche Solheim, A., van Wichelen, J. & Cardoso, A.C. (2013) Sustaining recreational quality of European lakes: minimizing the health risks from algal blooms through phosphorus control. Journal of Applied Ecology, 50 (2). 315-323. 10.1111/1365-2664.12059

Collins, A.M., Coughlin, D., Miller, J., Kirk, S. 2015. The Production of Quick Scoping Reviews and Rapid Evidence Assessments: A How to Guide. Defra, London

COMEAP (2009) Long-Term Exposure to Air Pollution: Effect on Mortality.

Department for Business, Energy & Industrial Strategy (2017) Energy trends: December 2016. Available at: www.gov.uk/government/statistics/energy-trends-december-2016.

Desholm, M., Fox, A.D., Beasley, P.D.L. & Kahlert, J., (2006) Remote techniques for counting and estimating the number of bird–wind turbine collisions at sea: a review. Ibis 148, 76–89.

Douvere, F. & Ehler, C.N. (2009) New perspectives on sea use management: Initial findings from European experience with marine spatial planning. Journal of Environmental Management 90, 77-88.

Drewitt, A.L. & Langston, R.H.W. (2006) Assessing the impacts of wind farms on birds. Ibis 148, 29-42.

Elliott P, Shaddick G, Wakefield JC, et al Long-term associations of outdoor air pollution with mortality in Great Britain Thorax 2007;62:1088-1094

European Union (2001) Council Directive 2001/42/EC of 27 June 2001 on the assessment of the effects of certain plans and programmes on the environment. Official Journal of the European Communities L197/30 (21/07/2001).

European Union (2009) Council Directive 2009/147/EC of 30 November 2009 on the Conservation of Wild Birds. Official Journal of the European Union L 20/7 (26.01.10).

Fowler, D., Skiba, U., Nemitz, E., Choubedar, F., Branford, D., Donovan, R., and Rowland, P. (2004) Measuring Aerosol and Heavy Metal Deposition on Urban Woodland and Grass Using Inventories of 210Pb and Metal Concentrations in Soil. *Water, Air and Soil Pollution: Focus* 4 (2-3), 483–499.

Fox, A.D., Desholm, M., Kahlert, J., Christensen, T.K. & Petersen, I.K. (2006) Information needs to support environmental impact assessment of the effects of European offshore wind farms on birds. Ibis 148, 129-144.

Freeman, S., Searle, K., Bogdanova, M.I., Wanless, S. & Daunt, F. (2014) Population dynamics of Forth & Tay breeding seabirds: review of available models and modelling of key breeding populations (MSQ – 0006). Report to Marine Scotland Science, 205 pp.

Furness, R.W. & Camphuysen, C.J. (1997) Seabirds as monitors of the marine environment. ICES Journal of Marine Science 54, 726–737.

Furness, R.W., Wade, H.M & Masden, E.A. (2013) Assessing vulnerability of marine bird populations to offshore wind farms. Journal of Environmental Management 119, 56-66.

Gallagher, M.W., Nemitz, E., Dorsey, J.R., Fowler, D., Sutton, M.A., Flynn, M. and Duyzer, J., 2002. Measurements and parameterizations of small aerosol deposition velocities to grassland, arable crops, and forest: Influence of surface roughness length on deposition. Journal of Geophysical Research: Atmospheres, 107(D12).

Gallopin, G.C. (1991) Human dimensions of global change: linking the global and the local processes. Int Soc Sci J 130: 707-718

Gurnell A.M. and Midgley P. (1994) . Aquatic weed growth and flow resistance - influence on the relationship between discharge and stage over a 25 year river gauging station record. Hydrol Process, 8, (1) 63-73. 10.1002/hyp.3360080105

Harrington R, Anton C, Dawson TP, de Bello, F, Feld CK, Haslett JR, Kluvankova-Oravska T, Kontogianni A, Lavorel S, Luck GW, Rounsevell MDA, Samways MJ, Settele J, Skourtos M, Spangenberg JH, Vandewalle M, Zobel M, Harrison PA (2010). Ecosystem services and biodiversity conservation: concepts and a glossary. Biodiversity and Conservation, 19: 2773-2790.

Heim, P., Hellmann, S., Lehmann, J., Lohmann, S., & Stegemann, T. (2009). RelFinder: Revealing Relationships in RDF Knowledge Bases. Semantic Multimedia. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-10543-2_21

Inger, R., Attrill, M.J., Bearhop, S., Broderick, A.C., Grecian, W.J., Hodgson, D.J., Mills, C., Sheehan, E., Votier, S.C., Witt, M.J., Godley, B.J. (2009) Marine renewable energy: potential benefits to biodiversity? An urgent call for research. Journal of Applied Ecology 46, 1145–1153.

Jackson, B., Pagella, T., Sinclair, F., Orellana, B., Henshaw, A., Reynolds, B., Mcintyre, N., Wheater, H., Eycott, A. (2013). Polyscape: A GIS mapping framework providing efficient and spatially explicit landscape-scale valuation of multiple ecosystem services, Landscape and Urban Planning, Volume 112, April 2013, Pages 74-88, https://doi.org/10.1016/j.landurbplan.2012.12.014

(http://www.sciencedirect.com/science/article/pii/S0169204612003532)Jones, L., Norton, L., Austin, Z., Browne, A.L., Donovan, D., Emmett, B.A., Grabowski, Z.J., Howard, D.C., Jones, J.P.G., Kenter, J.O. and Manley, W., 2016. Stocks and flows of natural and human-derived capital in ecosystem services. Land Use Policy, 52, pp.151-162.

Landers, D.H. and Nahlik, A.M. (2013). Final ecosystem goods and services classification system (FEGS-CS). *Epa United States Environmental Protection Agency: Washington, DC, USA*. https://gispub4.epa.gov/FEGS/FEGS-CS%20FINAL%20V.2.8a.pdf

Lindemann-Matthies P, Junge X, Matthies D. 2010. The influence of plant diversity on people's perception and aesthetic appreciation of grassland vegetation. Biological Conservation 143: 195–202.

Marine Management Organisation (2017) Marine Licensing: impact assessments. Available at: https://www.gov.uk/guidance/marine-licensing-impact-assessments.

Masden, E.A. & Cook, A.S.C.P (2016) Avian collision risk models for wind energy impact assessments. Environmental Impact Assessment Review 56, 43-49.

Matyssek, R., Sandermann Jr., H., (2003). Impact of ozone on trees: an ecophysiological perspective. In: Progress in Botany, vol. 64. Springer Verlag, Heidelberg. 349–404

McDonald, A. G., Bealey, W. J., Fowler, D., Dragosits, U., Skiba, U., Smith, R. I., Donovan, R. G., Brett, H. E., Hewitt, C. N., and Nemitz, E. (2007) Quantifying the effect of urban tree planting on concentrations and depositions of PM10 in two UK conurbations. *Atmospheric Environment* 41, 8455-8467.

McGahey, C., Samuels, P.G., Knight, D. and O'Hare, M.T. (2008). Estimating river flow capacity in practice. Journal of Flood Risk Management, 1 (1). pp. 23-33.

Mills, G., Pleijel, H., Braun, S., Büker, P., Bermejo, V., Calvo, E., Danielsson, H., Emberson, L., González Fernández, I., Grünhage, L., Harmens, H., Hayes, F., Karlsson, P.-E., Simpson, D. (2011). New stomatal fluxbased critical levels for ozone effects on vegetation. Atmospheric Environment 45: 5064-5068.

May, L. Taylor, P. and Spears, B. (2015). Decision support system to identify lakes likely to respond to agricultural diffuse pollution mitigation measures. Report to Defra, 17 pp.

Nordin, A., Näsholm, T. and Ericson, L. (1998), Effects of simulated N deposition on understorey vegetation of a boreal coniferous forest. Functional Ecology, 12: 691–699. doi:10.1046/j.1365-2435.1998.00240.x

Nowak, D. J. (2000). Impact of urban forest management on air pollution and greenhouse gases. In: Proceedings of the Society of American Foresters 1999 national convention; 1999 September 11–15; Portland, OR. SAF Publ. 00-1. Bethesda, MD: Society of American Foresters: pp. 143–148.Nowak D.J., Crane DE, Stevens JC (2006) Air pollution removal by urban trees and shrubs in the United States. *Urban Forest Urban Greening* 4:115–123.

Nowak, D.J., Hirabayashi, S., Bodine, A. and Greenfield, E., 2014. Tree and forest effects on air quality and human health in the United States. *Environmental Pollution*, 193, pp.119-129.

O'Hare, M.T., Clarke, R.T., Bowes, M.J., Cailes, C., Henville, P., Bissett, N., McGahey, C., Neal, M. 2010. Eutrophication impacts on a river macrophyte. Aquatic Botany, 92 (3). 173-178. 10.1016/j.aquabot.2009.11.001

O'Hare, J.M., O'Hare, M.T., Gurnell, A.M., Dunbar, M.J., Scarlett, P.M., Laize, C. 2011. Physical constraints on the distribution of macrophytes linked with flow and sediment dynamics in British rivers. River Research and Applications, 27 (6). 671-683. 10.1002/rra.1379

O'Hare, M.T. 2015. Aquatic vegetation - a primer for hydrodynamic specialists. Journal of Hydraulic Research, 53 (6). 687-698. 10.1080/00221686.2015.1090493

Paoletti, E., 2006. Impact of ozone on Mediterranean forests: a review. Environmental Pollution 144, 463–474.

Pope, C.A., Burnett, R.T., Thun, M.J., Calle, E.E., Krewski, D., Ito, K., Thurston, G.D. (2002) Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. *J. Am. Med. Assoc*, 287, 1132-1141

Potschin, M., Haines-Young, R. (2011). Ecosystem services: Exploring a geographical perspective. Progress in Physical Geography, 35(5): 575-594

Redhead, J.W.; Stratford, C.; Sharps, K.; Jones, L.; Ziv, G.; Clarke, D.; Oliver, T.H.; Bullock, J.M.. 2016 Empirical validation of the InVEST water yield ecosystem service model at a national scale. Science of the Total Environment, 569–570. 1418-1426. 10.1016/j.scitotenv.2016.06.227

RenewableUK (2013) Working for a Green Britain & Northern Ireland 2013-2023. Employment in the UK Wind & Marine Energy Industries. RenewableUK report, 51 pp.

Rounsevell , M.D.A., Dawson, T.P., Harrison, P.A. (2010). A conceptual framework to assess the effects of environmental change on ecosystem services. Biodiversity and Conservation, 19: 2823-2842

Rowe, R., Reis, S., Cooper, D., Williams, R., van Oijen, M., Fowler, D., Dore, T., Dragosits, U., Howard, D., Blyth, E., Norton, L., Wadsworth, R., O'Hare, M. & Harding, R. (2012). Towards a modelling strategy for CEH. Unpublished internal report

Saarikoski H, Jax K, Harrison PA, Primmer E, Mononen L, Vihervaara P, Barton D, Furman E (2015). Exploring operational ecosystem service definitions: the case of boreal forests. Ecosystem Services, 14: 144-157, doi:10.1016/j.ecoser.2015.03.006

Salvidge, R. 2017. How can we cost nature? ENDS Report, 505 (http://www.endsreport.com/article/55574/how-can-we-cost-nature)

Searle, K., Mobbs, D., Butler, A., Bogdanova, M.I., Freeman, S., Wanless, S. & Daunt, F. (2014) Population consequences of displacement from proposed offshore wind energy developments for seabirds breeding at Scottish SPAs. Contract report to Marine Scotland Science (CR/2012/03), 147 pp.

Sharps, Katrina; Masante, Dario; Thomas, Amy; Jackson, Bethanna; Redhead, John; May, Linda; Prosser, Havard; Cosby, Bernard; Emmett, Bridget; Jones, Laurence. 2017 Comparing strengths and weaknesses of three ecosystem services modelling tools in a diverse UK river catchment. Science of the Total Environment, 584-585. 118-130. 10.1016/j.scitotenv.2016.12.160

Simpson, D., Benedictow, A., Berge, H., Bergström, R., Emberson, L. D., Fagerli, H., Flechard, C. R., Hayman, G. D., Gauss, M., Jonson, J. E., Jenkin, M. E., Nyíri, A., Richter, C., Semeena, V. S., Tsyro, S., Tuovinen, J.-P., Valdebenito, Á., and Wind, P.: The EMEP MSC-W chemical transport model – technical description, Atmos. Chem. Phys., 12, 7825-7865, doi:10.5194/acp-12-7825-2012, 2012

Skärby, L., Ro-Poulsen, H., Wellburn, F. A. M. and Sheppard, L. J. (1998), Impacts of ozone on forests: a European perspective. New Phytologist, 139: 109–122. doi:10.1046/j.1469-8137.1998.00184.x

Tallis, H., Mooney, H., Andelman, S., Balvanera, P., Cramer, W., Karp, D., Polasky, S., Reyers, B., Ricketts, T., Running, S. and Thonicke, K. (2012). A global system for monitoring ecosystem service change. Bioscience, 62(11), pp.977-986.

van Oudenhoven, A.P.E., Petz, K., Alkemade, R., de Groot, R.S., Hein, L. (2012). Framework for systematic indicator selection to assess effects of land management on ecosystem services, Ecological Indicators, doi:10.1016/j.ecolind.2012.01.012

Wade, P.M. (1990). The colonization of disturbed fresh-water habitats by characeae. Folia Geobotanica & Phytotaxonomica 25: 275-278.

WHO 2006. Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulphur dioxide. Global update 2005. World Health Organization, Regional Office for Europe, Copenhagen, Denmark.

Wooller, R.D., Bradley, J.S. & Croxall, J.P. (1992) Long-term population studies of seabirds. Trends in Ecology and Evolution 7, 111-114.

12.2 Web links

ARIES model: http://aries.integratedmodelling.org/

Biological Records Centre (BRC): www.brc.ac.uk

CAMMP: www.cammp.org.uk/

CEDA: http://www.ceda.ac.uk/

CEH Land Cover Map: https://www.ceh.ac.uk/services/land-cover-map-2007

Countryside Survey (CS): http://www.countrysidesurvey.org.uk/

Countryside Survey Integrated Assessment: http://www.countrysidesurvey.org.uk/content/integrated-assessment

Ecomaps: See this video https://www.ceh.ac.uk/news-and-media/blogs/mapping-natural-capital for information and example outputs/applications

EMEP4UK: www.emep4uk.ceh.ac.uk/

Ecosystems Knowledge Network (EKN): http://ecosystemsknowledge.net/

Environmental Change Network (ECN): www.ecn.ac.uk

Glastir Monitoring and Evaluation project (GMEP): https://gmep.wales/

GraphDB (an RDF triple store solution): http://www.graphdb.net/

InVEST model: http://www.naturalcapitalproject.org/invest/

iRecord and other CEH citizen science apps: https://www.ceh.ac.uk/citizen-science-apps

LUCI model: http://lucitools.org/

National Biodiversity Network (NBN): https://nbn.org.uk/

National Plant Monitoring Scheme (NPMS): http://www.npms.org.uk/

Natural Capital Committee (NCC): https://www.gov.uk/government/groups/natural-capital-committee

Natural Capital Initiative (NCI): http://www.naturalcapitalinitiative.org.uk/

OpenNESS Project: http://www.openness-project.eu/

OS Mastermap: https://www.ordnancesurvey.co.uk/business-and-government/products/mastermap-products.html

RelFinder: http://www.visualdataweb.org/relfinder.php

Royal Society of Biology: http://www.rsb.org.uk/

SEEA methodology: https://unstats.un.org/unsd/envaccounting/seea.asp

UK lakes portal: https://eip.ceh.ac.uk/apps/lakes

UK Office of National Statistics (ONS): https://www.ons.gov.uk/

UK Rivers Network: http://www.ukrivers.net/

UNECE Convention on Long-range Transboundary Air Pollution (CRLTAP): https://www.unece.org/env/lrtap/welcome.html

Valuing Nature programme: http://valuing-nature.net/