Operationalisation of Natural Capital and Ecosystem Services

Database and operational classification system of ecosystem service – natural capital relationships

Deliverable D3.1 / WP3

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SEVENTH FRAMEWORK PROGRAMME

From concepts to real-world applications
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Summary

One of the objectives of OpenNESS is to investigate the ways in which natural capital (both biotic and abiotic components) underpins the delivery of ecosystem services. This report (deliverable under Task 3.1 in Work Package 3) approaches this objective by providing scientific evidence for the linkages between natural capital and ecosystem services based on a systematic search of peer-reviewed literature across four provisioning, seven regulation and maintenance, and two cultural ecosystem services. Data from 780 relevant journal articles published in English language was extracted into a spatial database structured according to a simple classification system which enabled analysis of the links between biotic (including biodiversity) and abiotic factors and associated ecosystem service providers for particular ecosystem types and geographical locations. The database also recorded any indicators measuring actual or potential ecosystem service delivery, as well as the impact of human activities and policies. Finally, it considered positive or negative interactions between the ecosystem services as reported in the papers, and the existence of any biophysical thresholds. A number of robust conclusions have emerged based on the analysis of the database results:

1. There is a general lack of literature explicitly addressing the relationship between natural capital attributes and ecosystem services.

2. Most of the biotic attributes identified in the review have a beneficial impact on ecosystem service delivery. Their contribution is related to three different clusters of attributes. The most commonly identified cluster relates to the *physical amount of vegetation* within an ecosystem, and includes habitat area, vegetation productivity, above- and below-ground biomass, stem density, species size/weight, growth rate, and successional stage. These tend to have beneficial impacts on a particular group of regulating services: atmospheric regulation (carbon storage), water flow regulation (flood protection), mass flow regulation (erosion prevention), water quality regulation (water purification) and air quality regulation. The second cluster focuses on the *presence or abundance of particular species or functional groups*. This is particularly important for the provision of freshwater fishing, timber, species-based recreation, pollination and pest regulation; a number of species-level traits (such as size or predation behaviour) are important for determining which are the most effective contributors to the ecosystem service. A third cluster, though less commonly discussed, comprises *diversity-related indicators*: species richness, species population diversity, functional richness, functional diversity, structural complexity and landscape diversity. Diversity is shown to be important for a wide range of services, including timber production, atmospheric regulation, pest regulation and pollination. It contributes to these services in two ways: niche complementarity, where efficiency is maximised because different organisms occupy different ecological niches; and the selection effect, where the presence of a wide range of different species improves the chance that one of them will be a high performer. Both of these mechanisms are shown to be important in different circumstances. Species richness and structural diversity also increase human enjoyment of species-based recreation and landscape aesthetics. There is also some mention of the role of diversity in ensuring resilience to environmental change.

3. Only a few biotic attributes had a negative impact on ecosystem service provision. These were: species mortality rate; the abundance of certain non-native species (e.g. invasive vegetation); the presence of forest plantations which can have a negative impact on freshwater supply; and a

limited number of examples where diversity had a negative effect because monocultures were found to provide a better service than polycultures.

4. Abiotic factors affect the delivery of ecosystem services, but their impact varies widely depending on the context. We found examples of both positive and negative effects as well as a large number of studies where the direction of the impact is unclear. Climatic factors are particularly relevant abiotic factors because they influence ecosystem dynamics, and exposure to climatic conditions outside a given range can limit the provision of ecosystem services. Temperature, precipitation and evaporation were cited frequently as important climatic factors for the services of water supply, food provision, air quality regulation, mass flow regulation and water flow regulation. In particular, many articles assess how climate change might impair delivery of ecosystem services in the future. Other important abiotic factors include the impact of slope on mass flow regulation and the influence of soil on food production and water supply.

5. Human activities are shown to have a range of positive and negative impacts on ecosystem service delivery, and many studies cite a mix of both. Overall, loss or damage of ecosystems through urban development, or over-exploitation of services (e.g. through intensive agriculture, deforestation or excessive eco-tourism), can alter the functioning of ecosystems and reduce the services they deliver. However, there are also many examples of ways in which protection, restoration and sustainable management of habitats can actively enhance ecosystem service delivery. Careful regulation and sustainable management offer opportunities to minimise the negative impacts of over-exploitation.

6. Ecosystem service delivery depends not only on the factors affecting a particular service, but also on the interactions with other services. It is crucial to assess bundles of services to understand the potential provision of individual services. Interactions between ecosystem services are mentioned in 40% of the articles reviewed, and 56% of these interactions are positive, highlighting the multiple benefits that ecosystems can provide. For example, forests can simultaneously provide many regulating services (atmospheric, water flow, mass flow, water quality) and cultural services (recreation and aesthetic landscapes). However, there are also some important negative interactions between services, especially between provisioning services and regulating or cultural services. These negative interactions are usually linked to human management activities that benefit one service but at the same time have negative impacts on another. Commonly cited examples include fertiliser application, which benefits food and timber production but has negative impacts on water quality regulation and freshwater fishing. Similarly, harvesting forests for timber has a negative impact on atmospheric regulation, water flow regulation and landscape aesthetics. Some management options may have short-term benefits but may result in adverse consequences in the long-term (such as a decline in pollinators and thus increased risks to food security due to intensive farming). Improved analysis of these interactions could help decision-makers to develop management strategies that exploit synergies and balance trade-offs more effectively.

The results of this review are useful in several ways:

1. Overall, the review emphasises the importance of conserving natural capital in order to continue to deliver robust and resilient ecosystem services in a world with increasing human demands. It also

provides valuable information on the contribution of different species, habitats and management techniques to the delivery of ecosystem services.

2. Within OpenNESS, this knowledge base can now be used to improve the design and selection of data for the ecosystem service mapping and modelling methods being developed in OpenNESS (Task 3.2), and the accompanying guidance (Task 3.4), both of which will be applied within the case studies (Work Package 5). Ultimately, a refined version of these tools, datasets and guidance will form part of the final OpenNESS contribution to the Oppla common platform (www.oppla.eu) for future application by the wider user community.

3. When focusing on the operationalisation of the concepts of natural capital and ecosystem services, this information base can help local decision-makers to identify opportunities for protecting and enhancing vital ecosystem services in their area, and for maximising positive interactions and minimising negative interactions between services, whilst national and regional policy-makers can design effective policies to facilitate these goals at a wider scale. Careful policy design is urgently needed to balance trade-offs between provisioning and regulating or cultural services that are linked to human decisions, and to protect ecosystems against future climate change and urban development. To preserve a balanced mix of ecosystem services as well as a healthy underlying level of biodiversity to sustain future services, it will be necessary to protect certain key habitats such as wetlands and old-growth forests from over-exploitation.

This updated version of D3.1 reflects an increase in the number of papers reviewed, to bring the number of papers reviewed for each ecosystem service up to 60 papers. At the same time, the database was checked a single reviewer to ensure consistency and correct any errors and omissions.

1 Introduction

Natural capital encompasses the elements of nature that directly or indirectly produce value for people, including ecosystems, species, freshwater, land, minerals, air and oceans, as well as natural processes and functions. Despite the importance of protecting the natural capital and ecosystem services on which we all depend, there is no consistent framework for including these concepts in policy-making. The OpenNESS project aims to find ways of integrating these concepts into land, water and urban management in Europe.

As part of that goal, OpenNESS (Work Package 3) aims to develop approaches for mapping and modelling the biophysical structure and associated ecological functions underpinning the delivery of ecosystem services, such as the way in which forests or grassland contribute to flood protection or carbon storage. This knowledge base can then be used to assess the effectiveness of different policy mechanisms and management practices for sustaining ecosystem service delivery whilst conserving biodiversity.

This will be achieved through the following sub-objectives:

- To analyse the contribution of natural capital stocks to ecosystem service flows by identifying the structural and functional factors that link them in different contexts (Task 3.1);
- To develop or improve a range of spatially-explicit methods for investigating the effects of multiple drivers on ecosystem services supply (Task 3.2);
- To develop methods for comparing ecosystem service supply with biodiversity conservation objectives to inform sustainable management practices and test the effectiveness of financial and governance instruments for conserving both ecosystem services and biodiversity (Task 3.3); and
- To create a set of guidelines for application of these methods within the OpenNESS case studies (Task 3.4).

This deliverable presents the method and results related to the first sub-objective (Task 3.1) on analysing the contribution of natural capital stocks to ecosystem service flows. The starting point of this analysis is a comprehensive literature review, based on peer-reviewed scientific articles published in English, and building on the database compiled by the BESAFE project (Biodiversity and Ecosystem Services: Arguments for our Future Environment[1]), which was focused on the linkages between biodiversity and ecosystem services. The results of this review are then presented in a series of network diagrams, tables and graphs, using a simplified topology that allows easy visualisation of the links between natural capital and ecosystem services. The findings from the review will be used to provide guidance to the case studies on the biotic and abiotic attributes which support the services potentially of interest within their case (Task 3.4).

In the next section, we summarise the current state of knowledge on the linkages between natural capital and ecosystem services, and describe how OpenNESS aims to extend that knowledge. We then present the methodology and results of our analysis, discuss the results and summarise our conclusions. At the end of the report are six Annexes providing full details of the information that has been summarised in the main document, and finally the reference section listing all the literature mentioned.

[1] http://www.besafe-project.net/

1.1 Links between natural capital and ecosystem services: current knowledge

Ecosystems provide three types of service according to the CICES classification (Haines-Young and Potschin, 2013): provisioning (e.g. food), regulation and maintenance (e.g. water quality regulation, atmospheric regulation) and cultural (e.g. recreation). The importance of these services for human well-being is well known (e.g. Butler and Oluoch-Kosura, 2006; Costanza et al., 1997; Daily, 1997; de Groot et al., 2002). However, for most ecosystems, our understanding of the current status of the services they provide is poor (Millennium Ecosystem Assessment (MA), 2005; Harrison et al., 2010; UK NEA, 2011).

The role of biodiversity in underpinning the delivery of ecosystem services is well recognised (Diaz et al., 2006; MA, 2005), and our understanding of this relationship is increasing. Early work explored the contribution of habitats (Chan et al., 2006), individual species, and species-species and species-environment interactions (Balvanera et al., 2005) to ecosystem services. Recently there has been more emphasis on the role of functional diversity, which may be more significant than species richness in determining the properties of an ecosystem. Functional traits are properties of species, such as size, shape or behaviour, which determine their impact on ecosystem processes and their response to environmental change (De Bello et al., 2010; Diaz and Cabido, 2001). Analysis of these functional traits has been useful in identifying the way in which particular species contribute to ecosystem processes and services (e.g. Balvanera et al., 2006; Diaz et al., 2011; Fagan, et al., 2008; Gaston, 2000; Hooper et al., 2005; Lavorel and Grigulis, 2012; Lavorel, 2013; Luck et al., 2012).

As a result of these advances in research, it is now recognised that *Ecosystem Service Providers* can either be single species (such as a specialist pollinator), a functional group (such as parasitoid wasps for pest control) or an entire habitat (such as a forest for carbon storage) (Kremen, 2005; Luck et al., 2009). Building on this concept, a number of studies have started to address the crucial question of how loss of biodiversity will affect future provision of ecosystem services (Cardinale et al. 2006, 2012).

Despite these advances in research, our understanding of the role of biodiversity in ecosystem service provision is still limited (Balvanera et al., 2014; Mace et al., 2012; Schröter et al., 2014). Few studies cover a wide range of biotic attributes and ecosystem services, and very few use empirical evidence to investigate the role of biodiversity in providing ecosystem services (Mertz et al., 2007, Seppelt et al., 2011). As a result, the quantitative relationships between different aspects of biodiversity and ecosystem services are still poorly understood (Carpenter et al., 2009; Luck et al., 2009; de Bello et al., 2010, de Groot et al., 2010). There is even less evidence on the role of abiotic factors, and how they interact with biotic attributes to deliver different ecosystem services (Harrison et al., 2014).

In particular, we need to understand the possible effects of natural capital loss on the delivery of ecosystem services. This is important in view of the possible existence of thresholds or tipping points at which natural capital loss severely compromises ecosystem service delivery. These have been demonstrated for some situations mainly focused on biodiversity variables (e.g. Scheffer, 2009), but we lack an understanding of how they might vary for different functions and services (Groffman et al., 2006) and under different abiotic conditions. Further evidence is essential so that services, and their underpinning natural capital, can be managed and monitored. A stronger evidence base could also support arguments for ecological restoration (Rey Benayas et al., 2009; Bullock et al., 2011), and contribute to the management of protected and

restored areas (Bastian, 2013) in order to meet the dual goal of conserving natural capital and biodiversity whilst optimising the delivery of ecosystem services (Palomo et al., 2014).

OpenNESS addresses this challenge and advances the state-of-the-art by evaluating, consolidating and expanding existing datasets on natural capital stocks (relevant biotic attributes and abiotic factors) and ecosystem service flows, including information on ecological thresholds. The work builds on the database generated by the BESAFE project (Harrison et al., 2014), which captures many journal articles from previous EU-funded projects, such as the FP6 RUBICODE project, to analyse linkages between biodiversity attributes and 11 ecosystem services. In OpenNESS, we have extended the conceptual framework used by BESAFE to enable analysis of additional factors including:

- Geographical co-ordinates of the locations of the reported studies, to enable spatial analysis and mapping;
- Direction of relationships between abiotic factors, as well as biotic attributes, and ecosystem services;
- Interactions (synergies and trade-offs) between different ecosystem services;
- The impact of human interventions and policies; and
- Evidence for thresholds or tipping points where further natural capital loss would severely compromise ecosystem functioning and service delivery.

Using the database, we analysed the relationships between natural capital and ecosystem services, applying a typology (or operational classification) that can reduce complexity and thereby help to put the ecosystem services concept into practice. This was used to guide the development and testing of a set of methods for mapping and modelling spatially-explicit ecosystem services supply in further OpenNESS work (Task 3.2).

2 Methods

The OpenNESS analysis aimed to complement and supplement previous work by activities such as TEEB, the FP6 RUBICODE project and the FP7 BESAFE project. The starting point was therefore a survey of all relevant completed and ongoing projects (including EU funded projects), databases and expert knowledge from the OpenNESS scientific community. This determined that the most efficient approach, to avoid duplicating previous work, was to extend and update the BESAFE database, which holds data on the relationship between biodiversity attributes and ecosystem services from approximately 50 peer-reviewed scientific journal articles for each of 11 ecosystem services, covering the period up to late 2012. We extended this work in eight ways:

1. Two additional ecosystem services were added - air quality regulation and food production (cultivated crops) - to address the main ecosystem services identified as important for the OpenNESS case studies. This brought the total number of services covered to 13.
2. Further biotic components were added based on the gaps identified in the BESAFE review.
3. The direction of relationships between abiotic components and ecosystem services was recorded to fully capture linkages between natural capital and service delivery.
4. Positive and negative interactions between ecosystem services were recorded.

5. New information on thresholds or tipping points, indicators, the impact of human activity and policy were extracted from the articles.
6. A new database tool was designed, including these additional factors to enable more in-depth analysis.
7. Records were transferred from the BESAFE database and each article was re-analysed to extract data for the new fields. The content was updated by adding at least ten recent articles for most of the ecosystem services, to cover the period from late 2012 to mid-2014. Additional articles were added if necessary to bring the total number for each service up to 60.
8. The database was extensively analysed, including the creation of network diagrams, maps and summaries for each ecosystem service (in Annex 5).

Figure 1 shows the inter-linkages between the basic elements of our analysis using the ecosystem service cascade framework (De Groot et al., 2010; Potschin and Haines-Young, 2011), as adapted by Braat (2015).

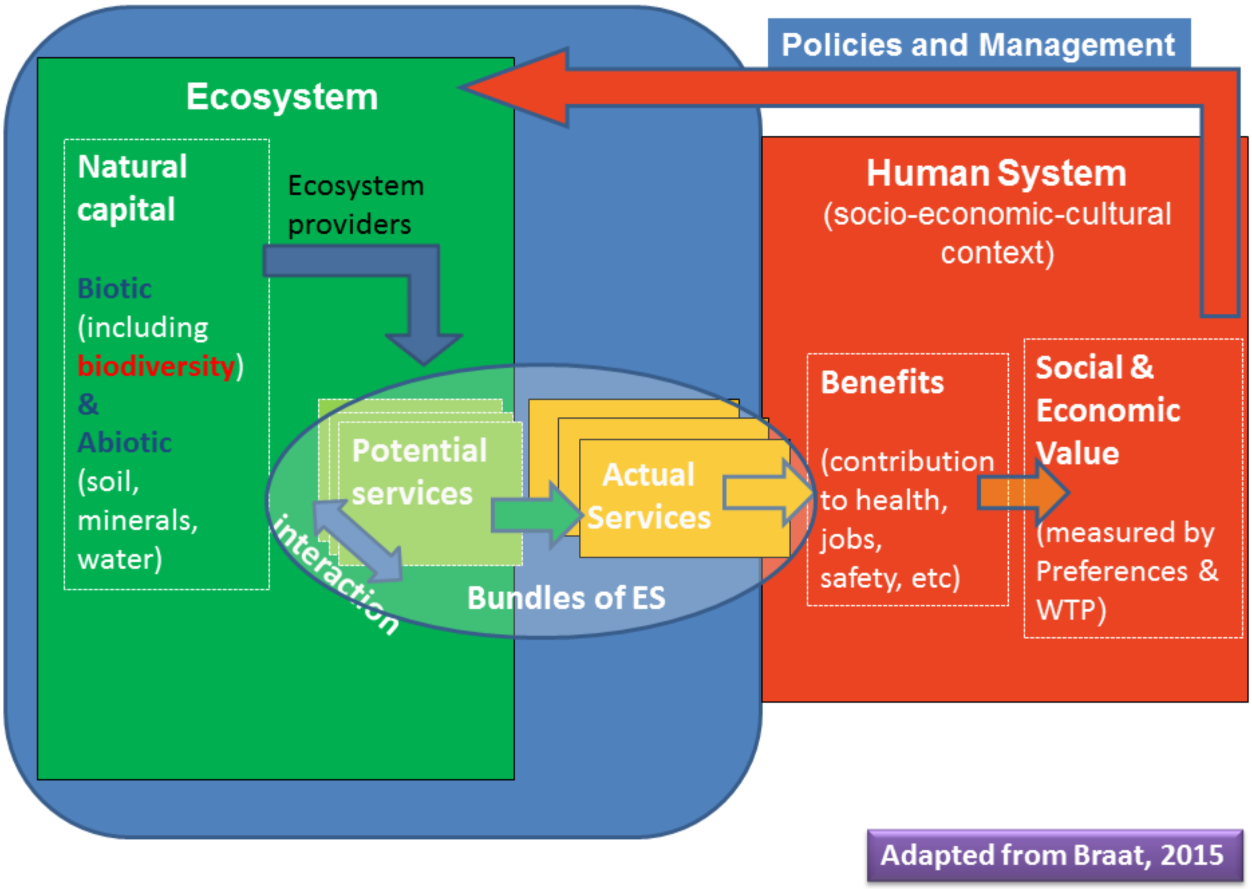

Figure 1: Inter-linkages between the basic elements of our analysis of the literature review, using the ecosystem service cascade conceptual framework. We focused on the Ecosystem and the underpinned ecosystem services (framed by a blue box), considering the policies and management options developed by the Human System as responses to the benefits received from the ecosystem services and their social and economic value. Within the Ecosystem, we analysed the Natural Capital (biotic attributes and abiotic factors) where ecosystem providers potentially deliver a bundle of ecosystem services that can turn into actual services if they are used by humans. We also assessed the interactions between ecosystem services.

In the following sections, we describe the methodology in more detail.

2.1 Selection of ecosystem services

Ecosystem services were selected to match those relevant to the OpenNESS case studies. It was not possible to cover all ecosystem services within the time and resources available, but 13 services were selected, covering 87% of those suggested as important for the case studies, excluding biodiversity which is considered as part of natural capital. Eleven of these services were already covered in the BESAFE database, and most of these journal articles were transferred to the new OpenNESS database tool. For the two additional services (food production and air quality regulation), a new literature search was carried out.

In total the report spans four provisioning services (freshwater fishing, timber production, freshwater supply, food production); seven regulation and maintenance services (air quality regulation, atmospheric regulation (carbon sequestration), mass flow regulation (erosion protection), water quality regulation (water purification), water flow regulation (flood protection), pollination and pest regulation); and two cultural services (species-based recreation and aesthetic landscapes). These are illustrated in Figure 2, which distinguishes the contribution of studies from OpenNESS and BESAFE to this review. Table 1 shows how these services relate to the CICES and Millennium Ecosystem Assessment classification schemes. Services relevant to the case studies that are not covered by the literature review are: bioenergy production (relevant to 4 case studies), cultural heritage (3), education (2), livestock (1) and local climate regulation (1). The category of “regulation and maintenance services” is sometimes abbreviated to “regulating services” in this report.

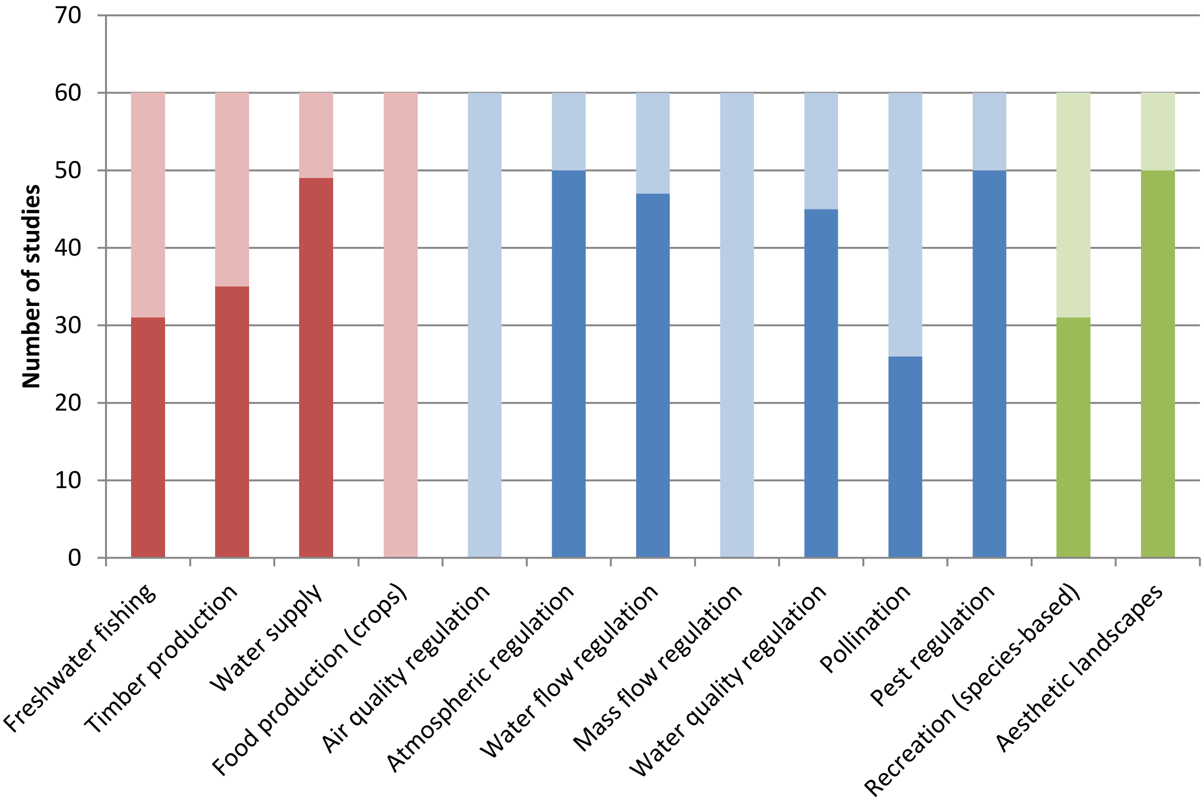

Figure 2: The number of studies included in this review per ecosystem service. This spans provisioning services (red), regulation and maintenance services (blue) and cultural services (green). Studies from the BESAFE review are indicated by the darker shades and new studies added during OpenNESS by the lighter shades. An article may include more than one study (see section 2.2).

Table 1: Links between the ecosystem service classes analysed in the literature review and the Millennium Ecosystem Assessment (MA) and CICES classifications.

	Ecosystem Service	MA	CICES group level	Note
Provisioning services	Freshwater fishing	Food (fodder)	Biomass [Nutrition]	
	Timber production	Fibre, timber	Biomass (fibres and other materials from plants, algae and animals for direct use and processing)	
	Water supply (quantity)	Freshwater	Water (for drinking purposes) [Nutrition]	CICES also has Water (for non-drinking purposes) [Materials]
	Food production (crops)	Food (fodder)	Biomass [Nutrition]	
Regulation and maintenance services	Air quality regulation	Air quality regulation	Dilution & sequestration [Filtration of particulates and aerosols]	
	Atmospheric regulation (carbon sequestration)	Climate regulation	Atmospheric composition and climate regulation	
	Mass flow regulation (erosion protection)	Erosion regulation	[Mediation of] mass flows	Has some overlap with water regulation
	Water flow regulation (flood protection)	Water regulation	[Mediation of] liquid flows	TEEB splits into Mediation of liquid flows and mediation of mass flows
	Water quality regulation (water purification)	Water purification and water treatment	Mediation [of waste, toxics and other nuisances] by biota and Mediation [of waste, toxics and other nuisances] by ecosystems	Under this category CICES also has Mediation of gaseous/air flows
	Pollination	Pollination	Lifecycle maintenance, habitat and gene pool protection	
	Pest regulation	Biological control	Pest and disease control [Biological control mechanisms]	
Cultural services	Recreation (species-based)	Recreation and ecotourism	Physical and experiential interactions	
	Aesthetic landscapes	Aesthetic values	Intellectual and representational interactions	

2.2 Development of OpenNESS database tool

A new database tool was developed to summarise the results of the literature review. The aim was to capture the contribution that both biotic and abiotic aspects of natural capital make to the delivery of specified ecosystem services at different spatial and temporal scales. It is intended that the database will form part of 'Oppla', a shared web-platform with our twin project OPERAs.

The database includes the following information:

- the ecosystem service;
- the reference;
- the geographical co-ordinates of the location of the study (as a place name), to enable the spatial analysis and mapping of ecosystem services;
- interactions between different ecosystem services;
- the spatial scale;
- the temporal scale;
- type and condition of ecosystems, including whether they are actively managed;
- the ecosystem service provider (ESP);
- the important biotic attributes of the ESP, and direction of relationship;
- presence of abiotic factors which affect service delivery and their direction of influence;
- human input and management;
- indicators used to assess and quantify the ecosystem service;
- evidence for thresholds or tipping points;
- policies mentioned by the article;
- a rating of the overall strength of the evidence.

Further details on each of these data categories are presented below. Data were entered into a software tool consisting of a WinForms user interface linked to a Microsoft Access database. Full details of the tool, including screenshots, are presented in Annex 6. The main screen of the tool and the spatial location entry screen are shown in Figure 3 below.

Some journal articles were split into separate studies, which were entered separately into the database. This was done where articles addressed more than one ecosystem, location or ecosystem service provider, and the conclusions were significantly different in each case. Some articles were also relevant to more than one ecosystem service. Thus each journal article can have more than one database entry. For consistency, the individual database entries are referred to as "studies" throughout this document. The database contains 780 studies in total, derived from 755 journal articles. It is also possible for each database entry to have more than one study location – these are referred to as "study sites". There are 939 study sites entered into the database.

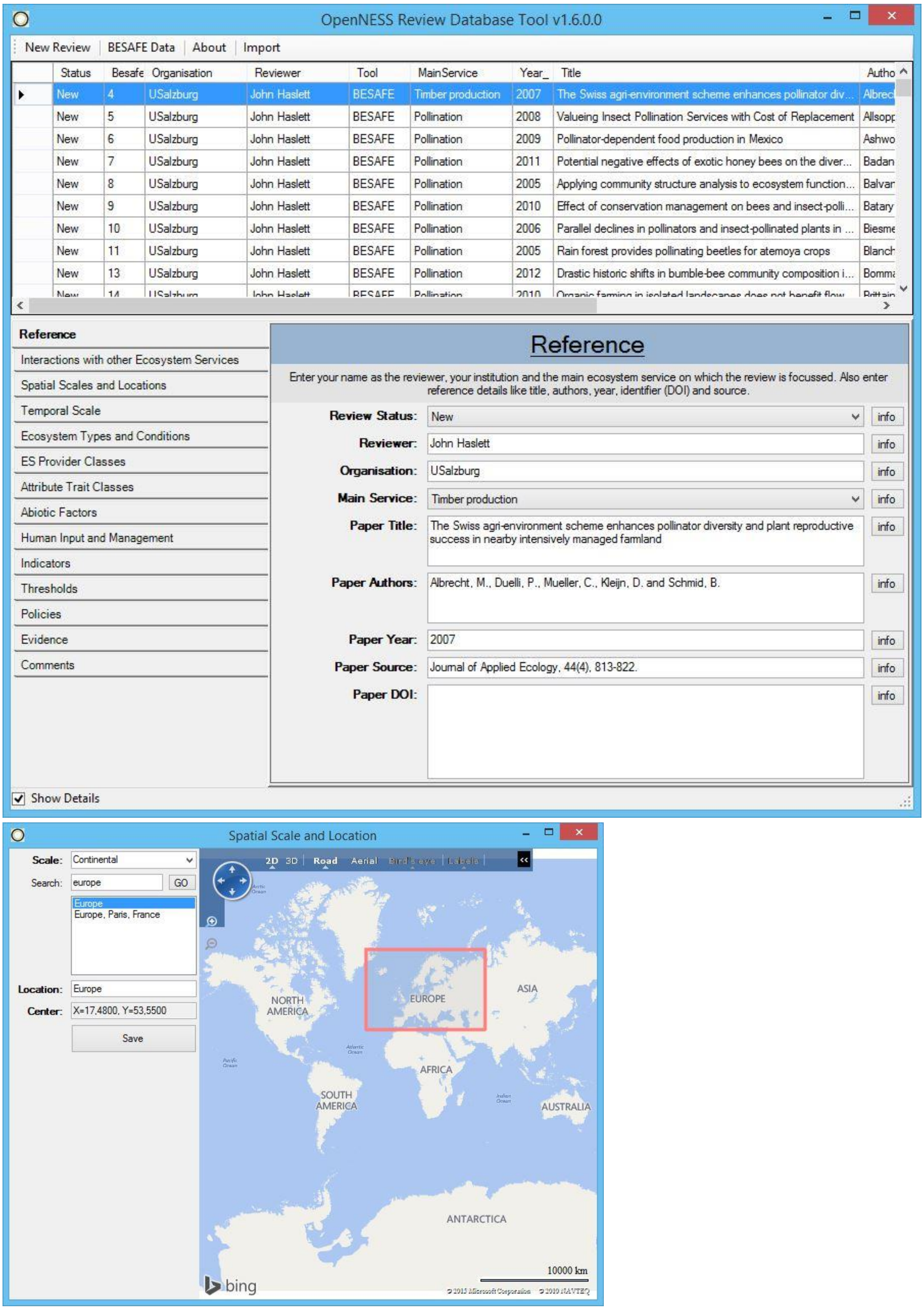

Figure 3: The main screen and the spatial location entry screen of the OpenNESS database tool.

2.2.1 Ecosystem service

This records which of the 13 ecosystem services is being reviewed. The selection of the ecosystem services to be included in this review is discussed in Section 2.1.

2.2.2 Reference

This records the reviewer's name and institution, and the article title, source, authors, year of publication and DOI. The DOI will be used for automatic linking to online resources through the Oppla web platform.

2.2.3 Interactions with other ecosystem services

This stores the types of relationship between the main ecosystem service and any other ecosystem services that are mentioned in the article. The relationship can be positive, negative, both (positive and negative) or unclear (the article mentions the service being affected, but does not give an indication of the direction). Free text boxes are provided to add additional information on the nature of the relationship and to capture any quantitative information.

2.2.4 Spatial scales and locations:

This records the spatial scale and location of the study. The scale is selected from a drop-down list of the six following options:

- Local (single land parcel, farm or sub-catchment);
- Sub-national (anything in between local and national, but not including them);
- National;
- Sub-continental (anything in between national and continental, but not including them);
- Continental (Asia, Africa, North America, South America, Antarctica, Australia or Europe);
- Global.

Location is identified using a search box in which the user can enter either a place name or geographical co-ordinates (see Figure 3). A pop-up map window (powered by a Microsoft application using Bing maps) then shows the location. The geographical location is registered as the bounding box shown in the map window. If the study covers more than one location or study site, additional locations can be added.

2.2.5 Temporal scale

If the article mentions the temporal scale of the study (i.e. the period of observations, experiments or model simulations) it can be entered here as either:

- Snapshot;
- Seasonal;
- Annual;
- Long-term;
- Scenario analysis.

If information is available on the start and end of the period of observation, experiment or simulation, it can be entered as day, month and year.

2.2.6 Ecosystem types and conditions

Any ecosystems mentioned in the article are recorded. There is a choice of 12 ecosystem types, based on level 2 of the ecosystem typology used in the MAES (Mapping and Assessment of Ecosystem and their

Services) Working Group[2]. This corresponds directly with the EUNIS habitat classification and SEBI 04 indicator on ecosystem coverage. It is relevant for EU policies and compatible with global ecosystem classifications. It is typological (enabling comparison between different parts of the European territory), keeps a (pan) European scale and takes into consideration regular mapping aspects (applying CORINE Land Cover (CLC) data for spatial delineation). Table 2 provides details of the ecosystem typology.

Table 2: Details of the ecosystem typology used in the database.

Major ecosystem category (level 1)	Ecosystem type for mapping and assessment (level 2)
Terrestrial	Urban
	Cropland
	Grassland
	Woodland and forest
	Heathland and shrub
	Sparsely vegetated land
	Wetlands
Fresh water	Rivers and lakes
Marine	Marine inlets and transitional waters
	Coastal
	Shelf
	Open ocean

In addition, the condition of all ecosystems mentioned in the article can be recorded (if known) using a classification modified from the English Nature Special Site of Scientific Interest (SSSI) classification scheme:

- *Condition not mentioned* (the ecosystem is mentioned, but no information is supplied about its ecological condition);
- *Favourable* (the ecosystem in question is being adequately conserved and is meeting its 'conservation objectives'. There may still be scope for enhancement, but there is no or very little ecological concern for this ecosystem);
- *Unfavourable - Recovering* (the ecosystem is not yet fully conserved, but there is evidence within the article that the ecological status is improving);
- *Unfavourable - No Change* (the ecosystem is not adequately conserved and the evidence within the article states that the ecological status is not changing);
- *Unfavourable - Declining* (the ecosystem is not adequately conserved and the evidence within the article suggests that the ecosystem condition is becoming progressively worse);
- *Unfavourable - No Evidence* (the ecosystem is not adequately conserved, but there is no evidence within the article as to the trajectory of change);
- *Destroyed* (the ecosystem existed at one point, but has been destroyed to the point that it would need to be re-created. The area is now considered as a different ecosystem type. This class includes both the Destroyed and Part-Destroyed classes of English Nature).

[2] An Analytical framework for ecosystem assessments under Action 5 of the EU Biodiversity Strategy to 2020, Discussion paper, Final, April 2013, European Union, 2013 ISBN 978-92-79-29369-6 DOI 10.2779/12398

There is also a “Conservation Management” box which can be ticked if the article reports that any conservation action is either planned or taking place with respect to the ecosystem in question. Free text boxes are provided for additional information on the type (e.g. coniferous forest, extensive grassland for livestock grazing) and condition (e.g. any specific evidence to support the class selected) of each ecosystem.

2.2.7 Ecosystem Service Provider (ESP) classes

The broad ecosystem services provider class is selected from a drop-down menu. ESPs are defined as the populations, functional groups or communities that contribute to service provision. The options are:

- *Single specific species population* (A group of organisms, all of the same species, which occupies a particular area (geographic population), is genetically distinct (genetic population) or fluctuates synchronously (demographic population));
- *Two or more specific species populations*;
- *Single functional group* (A collection of organisms with similar functional trait attributes in the study area, i.e. a feature of an organism, which has demonstrable links to the organism’s function. Sometimes referred to as a guild, especially when referring to animals);
- *Two or more functional groups*;
- *Entire community or habitat* (An association of interacting populations, usually defined by the nature of their interactions or by the place in which they live);
- *Two or more communities or habitats*;
- *Dominant community* (defined either qualitatively or quantitatively based on the article).

A free text box is provided to add more specific information on the ESP.

2.2.8 Biotic attributes/traits which affect ecosystem service delivery

This holds information about all the biotic attributes and traits mentioned in the article that are important for the provision of the ecosystem service. Together with the list of abiotic factors (described in section 2.2.9 below), this describes the natural capital.

There are two descriptors for each attribute:

- Direction of the relationship: not mentioned, positive, negative, both (positive and negative) and unclear (the article mentions the relationship, but does not clearly indicate the direction).
- Free text box to add information on specific qualitative or quantitative information from the article.

SPECIES ATTRIBUTES:

- Presence of a specific species type (name of the species can be added in the free text box)
- Species abundance (number of individuals of a species expressed per unit area or volume of space. Synonymous with species population density)
- Species richness (number of different species represented in a set or collection of individuals)
- Species population diversity (the number, size, density, distribution and genetic variability of populations of a given species)
- Species size or weight (includes body size or weight, diameter at breast height – DBH – for trees, species/vegetation/tree height, basal area defined as the cross section area of the stem or stems of

a plant or of all plants in a stand, generally expressed as square units per unit area) (free text box can specify the type of measurement)

- Population growth rate (change in the number of individuals of a species in a population over time)
- Mortality rate (number of deaths of individuals per unit time)
- Natality rate (number of new individuals produced per unit time)
- Life span/longevity (duration of existence of an individual/expected average life span)

FUNCTIONAL GROUP ATTRIBUTES:

- Presence of a specific functional group type (the name of the functional group(s) can be recorded in the free text box)
- Abundance of a specific functional group
- Functional richness (the number of functional groups or trait attributes in the community)
- Functional diversity (range, actual values and relative abundance of functional trait attributes in a given community)
- Flower-visiting behavioural traits well suited to the system to provide pollination ecosystem services (free text box allows the behavioural type/preference/strategy to be entered)
- Predator behavioural traits well suited to the system to provide biocontrol ecosystem services (free text box allows the behavioural type/preference/strategy to be entered)

COMMUNITY/HABITAT ATTRIBUTES:

- Presence of a specific community/habitat type (the name of the habitat(s) or ecosystem(s) can be entered in the free text box)
- Community/habitat area (includes width or diameter, i.e. for buffer zones)
- Community/habitat structure (in terms of complexity - amount of structure or variation attributable to absolute abundance of an individual structural component - and heterogeneity - kinds of structure or variation attributable to the relative abundance of different structural components)
- Primary productivity (rate at which plants and other photosynthetic organisms produce organic compounds in an ecosystem)
- Aboveground biomass (the total mass of aboveground living matter within a given area)
- Belowground biomass (the total mass of belowground living matter within a given area)
- Sapwood amount (including allocation of carbon to sapwood and sapwood area)
- Stem density (measured as the number of stems/specified area)
- Wood density (measured as the weight of a given volume of wood that has been air-dried)
- Successional stage (changes in the number of individuals of each species of a community by establishment of new species populations that may gradually replace the original inhabitants; categorised into early and late stages)
- Habitat/community/stand age (includes young and old-growth forests, even and uneven-aged forests, or can specify the age)
- Litter/crop residue quality (quality of plant litter with respect to decomposition: often defined by the C:N ratio, but ratios of C, N, lignin and polyphenols are other chemical properties and particle size and surface area to mass characteristics are physical properties)
- Leaf N content

OTHER ATTRIBUTES:

- Landscape diversity (diversity of landscapes and landscape features)
- Other (if an attribute or trait is mentioned that is not in this list, it can be added here and described in the free text box)

2.2.9 Abiotic factors which affect ecosystem service delivery

This allows the user to record information about all the abiotic factors mentioned in the article that are important for provision of the ecosystem service. The intention was to record only cases where an abiotic factor affects the ability of the ecosystem to deliver a service. For example, it is obvious that heavy rainfall can cause flooding, but this observation is not relevant for ecosystem service delivery. However, it is relevant to note whether the level of rainfall affects the ability of a forest or wetland to prevent flooding.

Similarly to the biotic attributes, the direction of the relationship (positive, negative, both or unclear) is recorded and there is a free text box for additional information. Abiotic factors are selected from the following list:

- Temperature
- Precipitation
- Evaporation
- Wind
- Snow
- Soil (direction not applicable but details of any influence can be recorded in the free text box)
- Geology (ditto)
- Water availability
- Water quality
- Nutrient availability (soil minerals)
- Slope (angle, aspect)
- Other (if an abiotic factor is mentioned that is not in this list, it can be added here and described in the free text box)

2.2.10 Human input and management

This records whether the article explicitly mentions any human inputs (in terms of either management or resource application) to the ecosystem, and whether these inputs are applied directly to the ecosystem or indirectly from neighbouring areas. A free text box is provided to give more specific details. Options include:

- Not mentioned (human management or input of resources are not mentioned in the article.)
- Direct human input (human inputs are explicitly mentioned in the article in terms of direct application of management or resources to the ecosystem. Also, there are no indirect human inputs mentioned.)
- Indirect human input (direct human inputs to the ecosystem are not mentioned in the article. However, management or resource application in neighbouring ecosystems/contexts is stated to be having an impact.)
- Both direct and indirect input (both direct and indirect inputs are explicitly mentioned in the article.)
- Unclear (human input is mentioned in the article, but it is unclear if it is direct or indirect.)

The intensity of human input or management is also recorded using the following options:

- None
- Intensive (if there is a significant use of capital and inputs relative to land area. To be classified as "Intensive" the article will mention that the main goal of the management is maximising production.)
- Extensive (if there is a low use of capital and inputs relative to land area. To be classified as "extensive" the article will mention that the land is not being managed to its utmost productive potential.)
- Intensive and extensive (if there is evidence of both intensive and extensive management within the article.)
- Unclear (if management is mentioned, but there is no indication as to the form this takes so that it is impossible to determine if intensive or extensive management is taking place.)

A free text box is provided to give more specific information on the intensity of human input or management.

Finally, there is a field to record the impact (in terms of direction) of management on the main ecosystem service and other ecosystem services mentioned in the article. A free text box is provided to give more specific details. Options include:

- Not mentioned
- Positive
- Negative
- Both (positive and negative)
- Unclear

2.2.11 Indicators

Information on any indicators used for assessing the main ecosystem service can be recorded. A list of potential indicators for each service is generated, based on the JRC report 'Indicators for mapping ecosystem services: a review' (Egoh et al., 2012) (see Annex 3). Other indicators not included in this list can also be added. For each indicator, a check box is ticked if it is used in the article and the following information is recorded:

- The assessment method used to calculate the indicator:
    - Primary data (the indicator is based on data from direct field observations or from public statistical databases)
    - Mechanistic model (the indicator is generated using a biophysical model of the ecosystem)
    - Correlative model (the indicator is estimated using a statistical relationship between primary data and environmental data)
    - Conceptual model (the indicator is based on an artificially defined rating or scoring system which reflects expert opinion)
- Units or dimensions of the indicator, in a free text box
- Information on any thresholds that are identified for the indicator, in a free text box
- A comment box is provided for any other specific information

2.2.12 Thresholds

This section records any information on thresholds that has not already been entered in the previous section for a particular indicator. There are three options:

- Other biophysical thresholds: biophysical thresholds not already included in the “Indicators” screen. These are defined as thresholds in ecological structures and/or functions that support ecosystem services, e.g. bumblebee density (no./ha) or farmland bird richness (no. species/ha).
- Safe minimum standards: a scientifically grounded limit to avoid the risk of reaching a threshold, although not necessarily legally binding, e.g. maximum concentration of air pollutants recommended by WHO.
- Legal boundaries: a legally binding threshold, e.g. prescriptive limits on air pollutants.

Free text boxes are provided for each type of threshold to add any descriptive and quantitative information provided in the article.

2.2.13 Policies

This section records any policies mentioned in the article. There is a list of 24 EU policies with check boxes and free text boxes to provide information on how the article refers to each relevant policy. These policies are selected from a list compiled within OpenNESS (Work Package 2). We tried to cover all the relevant sectors and at the same time keep the number manageable. More than one policy can be selected using check boxes:

- Biodiversity Strategy
- Green Infrastructure Strategy
- Birds Directive
- Habitat Directive
- Ambient Air Quality Directive
- Common Agriculture Policy
- Nitrates Directive
- Biocides Directive
- Plant Protection Products Regulation
- Common Fishery Policy (CFP)
- Rural Development Policy (2007-2013)
- Regulation on support for rural development by the European Agricultural Fund for Rural Development (EAFRD)
- Cohesion Policy (2014-2020)
- Water Framework Directive (WFD)
- Marine Strategy Framework Directive (MSFD)
- EU Floods Directive
- Renewable Energy Directive
- Forest Action Plan
- Thematic Strategy on the Urban Environment
- Environmental Impact Assessment
- Strategic Environmental Assessment
- EU Adaption Strategy

- Soil Thematic Strategy (2007-2011)
- Thematic Strategy on the Sustainable Use of Natural Resources
- Other (details entered in free text box, including national policies).

2.2.14 Evidence rating

Four questions are posed on the quality of the evidence within the article:

- Is the evidence qualitative, quantitative or both?
- Is the evidence based on a single or multiple observations?
- Is the evidence direct or indirect (i.e. through a surrogate)?
- Is the evidence based on empirical data, modelled information, or both?

A free text box is provided next to each question to explain the selection from the drop-down list.

2.2.15 Comments

Finally, there is a free text box for any additional comments that are important, but which are not covered by other parts of the database.

2.3 Literature search and data entry

Following development of the data entry tool, the existing studies from the BESAFE database (around 30 to 50 studies for each service) were transferred into the OpenNESS database. This involved re-analysing each article in order to extract information on the role that natural capital (rather than only biodiversity) had on ecosystem services, as well as the new data attributes mentioned in the previous section.

For the two new ecosystem services - air quality regulation and food production – a new literature search had to be carried out. This consisted of three stages: (i) generation of keywords; (ii) a systematic search; using Web of Science; and (iii) extraction of the data into the database.

For the other services, as the BESAFE database only covered the period up to mid-2012, the search was updated to identify at least 10 new articles for each service, covering the period from mid-2012 to mid-2014, and add more studies if necessary to bring the total number to 60 per service.

The search conformed to the methodology developed during the BESAFE project (Harrison et al., 2014). A pilot test showed that 'ecosystem services' is a relatively new term and, hence, only using this term in a literature search is likely to miss relevant articles. Thus, keywords specific to each ecosystem service were selected (e.g. "carbon storage"), accompanied by appropriate biodiversity terms which could be related to the given ecosystem service (e.g. "species richness"). Additional service-related terms were used if necessary to refine results when large numbers of articles were found for the initial search terms (e.g. "tree", "forest"). The full list of search terms is presented in the short reports for each ecosystem service (Annex 5).

Where fewer than 60 studies were identified for a service using the above methodology, additional intelligent search approaches were utilised. These included: (i) searching the reference lists of relevant

articles for secondary references which may be of interest (termed snowballing); and (ii) searching articles that have cited the relevant articles (termed reverse snowballing).

The standard search did not identify many examples of thresholds above which ecosystem services deteriorate. Therefore an additional literature search was carried out using the terms "ecosystem AND service AND threshold". The articles found were not entered into the database, but the supplementary review was used to inform the analysis of thresholds presented in the results section. Further details of this search and its results are given in Annex 1.

2.4 Network diagrams

Network diagrams were created for each ecosystem service, to explore the linkages between the biotic attributes and abiotic factors (natural capital) and the ecosystem service providers. Although the literature review distinguished between single and multiple ecosystem service providers (i.e. single species, multiple species; single functional group, multiple functional group; etc.) the network diagrams used a simpler typology based on just species, functional group or community/habitat. This was done to enable easier visual interpretation of the diagrams in order to create an operational classification for each service, and also because the analysis showed that the distinction between single and multiple ESPs did not affect the interpretation of the results. This is because the number of ESPs mentioned in an article is generally a function of the study design. Studies with multiple ESPs are usually comparing several species or habitats against each other, or simply choosing an arbitrary number of species to include in the experiment. The distinction between single and multiple ESPs does not therefore reflect the number of species or habitats required to provide the service.

The network diagrams demonstrate both the predominant direction of evidence for the relationship, which determines the colour of the lines, and the strength of the relationship (the proportion of studies for that ecosystem service which show that particular link), which determines the thickness of the lines. The direction of the relationship was calculated as shown in Table 3.

Table 3: Methodology to determine predominant direction of evidence for network diagrams.

Number of articles showing links that are:				Positive-Negative	Predominant direction	Colour of line
Positive	Both positive and negative	Negative	Unclear			
≥1	0	0	≥0	≥1	**Positive**	Dark green
≥1	≥1		≥0	≥1	**Mostly positive**	Light green
Positive-negative=0 AND/OR Unclear≥1				0	**Neutral**	Grey
≥1		≥1	≥0	≤1	**Mostly negative**	Light red
0	0	≥1	≥0	≤1	**Negative**	Red
0	0	0	0	0	No relationship	Not shown

The network diagrams were then created using the Pajek software (http://pajek.imfm.si/doku.php). Two examples are presented in the overview and synthesis of results (section 3), and the diagrams for each ecosystem service are presented in section 4.

3 Overview and synthesis of results

This section presents an overview and synthesis of the results. Section 4 then presents separate summaries for each of the 13 ecosystem services.

3.1 Location and spatial scale

The majority of the studies focus on sites in Europe (33%) or North America (26%), with 14% in Asia and considerably fewer from Africa, Oceania and South America (Figure 4). This may simply reflect the higher amount of research activity in Europe and North America, but could also be a consequence of the review focusing on journal articles written in English.

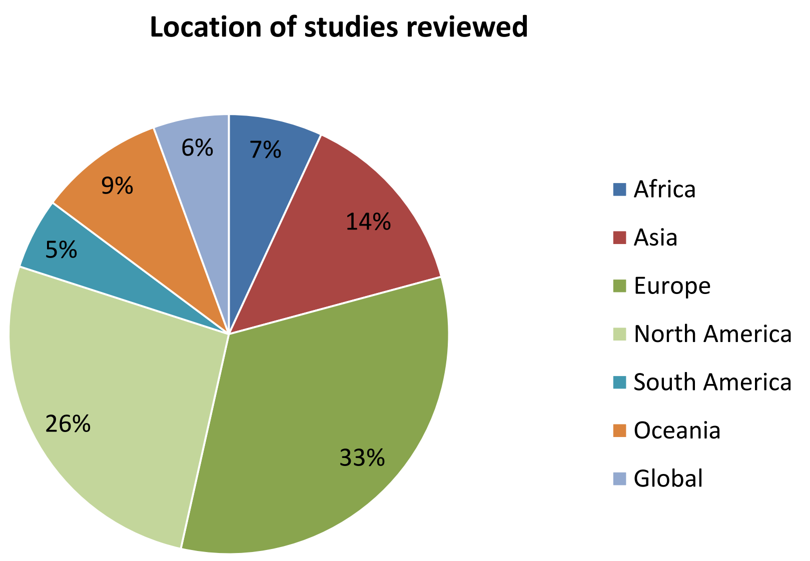

Figure 4: Location of the studies reviewed (% of study sites). Note that a study may cover more than one study site.

Figure 5 shows how the geographical distribution of the studies varies for the different ecosystem services. Note that some studies cover a variety of locations, so that there are 939 study sites across the 780 studies entered into the database. The bias towards Europe and North America is particularly apparent for air quality regulation, where 84% of study sites are in these locations, with most of the other services having 50–70% of studies in these regions. This probably reflects the higher air and water quality standards and the greater resources available for research in those regions. The only services where Europe and North America together account for less than 50% of the study sites are freshwater fishing, where 28% of study sites are in Asia (where aquaculture is an important industry); water supply, where 31% of study sites are in Oceania (reflecting the severity of water shortages in Australia); food production, where 28% of study sites are in Africa; and recreation, where the number of studies in Africa, Asia and Oceania indicate the importance of eco-tourism in these regions. However the figure also shows the importance of research on mass flow regulation and atmospheric regulation in Asia (especially China).

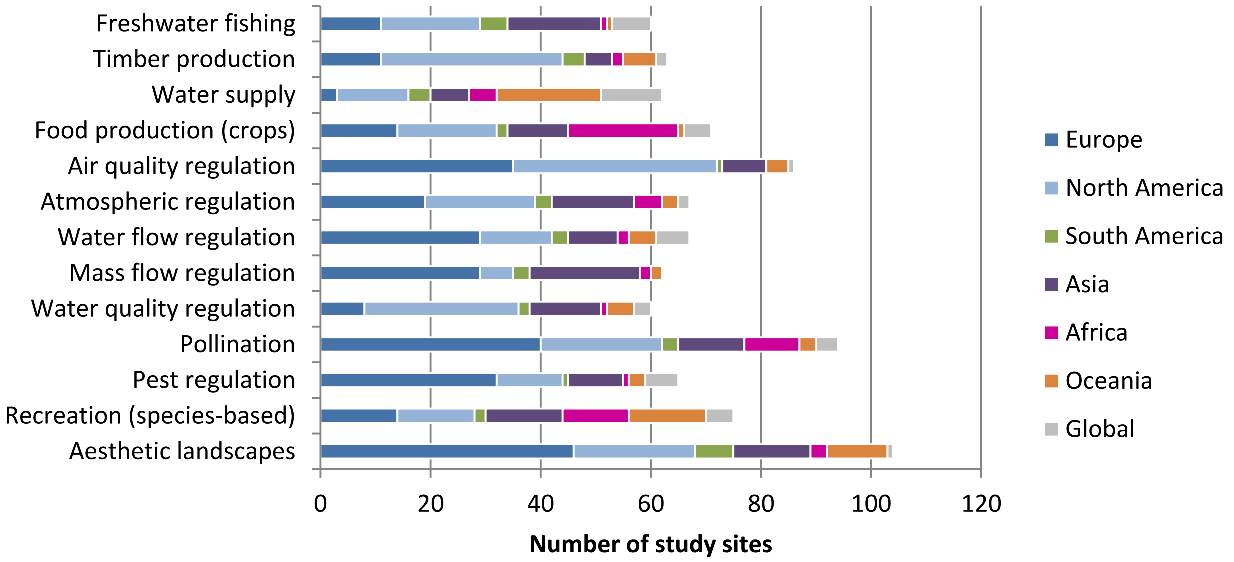

Figure 5: Location of studies by ecosystem service. Note that a study may have more than one study site.

The majority of articles reviewed focus on smaller scales, as shown in Figure 6. Most (58%) of the study sites were local, and 30% are sub-national. In contrast, just 5% of the sites were at a national scale, 1% at a continental scale and 6% at the global scale.

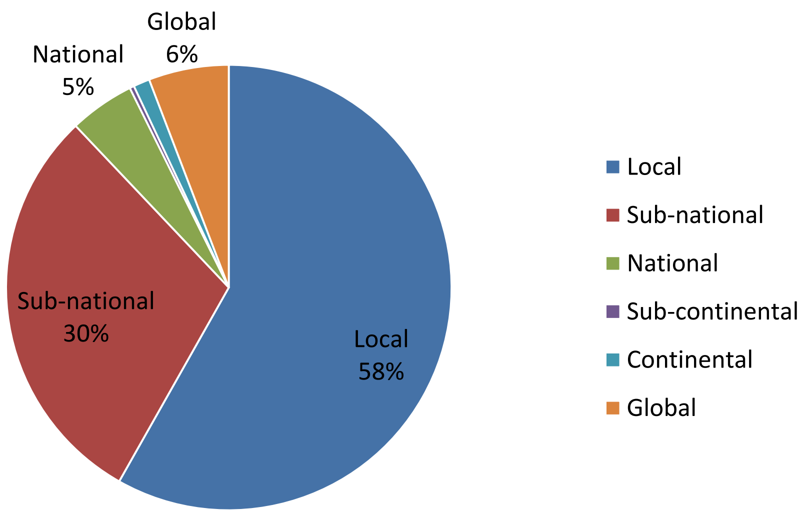

Figure 6: Number of study sites at each spatial scale across all ecosystem services.

Figure 7 shows the scale of the study sites for each ecosystem service. The tendency to focus on smaller scales is particularly true for mass flow and air quality regulation (where over 90% of studies are at the local scale). For atmospheric regulation, pollination, pest regulation, recreation, food and timber production, 60-70% are at the local scale with the remainder being mainly at the sub-national scale. This reflects the typical format of the studies, which tend to be experimental investigations at particular sites, or occasionally (e.g. for pest regulation) laboratory studies. For water flow regulation, water supply and freshwater fishing there

are more studies at sub-national scale, as many studies of these services are carried out at the level of a catchment. The lack of studies at larger scales indicates that it can be difficult to measure ecosystem service flows over large areas, because delivery of ecosystem services tends to be very specific to local conditions. The major exception is for aesthetic landscapes, where over 80% of the studies are at the sub-national scale and only 2% are at the local scale, reflecting the focus on evaluating landscapes at a broader spatial scale (e.g. through surveys of visitor preferences in national parks or protected areas, or by questioning people from a range of towns or cities).

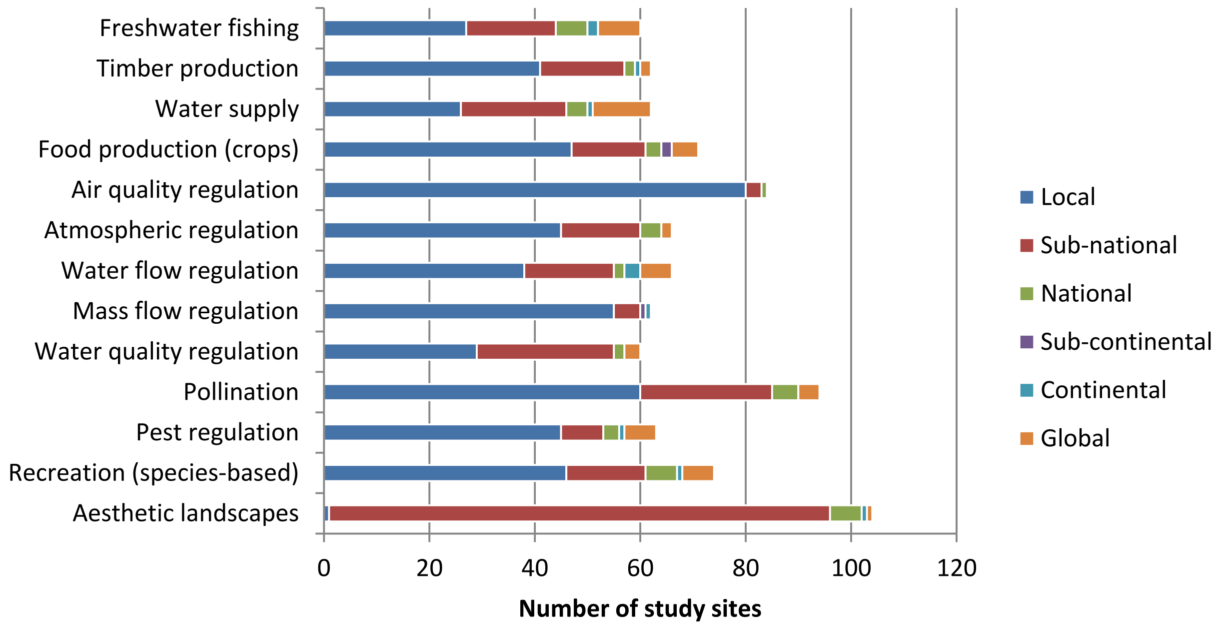

Figure 7. Study scale by ecosystem service (note there can be more than one site per study)

Most of the global studies are reviews, though there are some meta-analyses of global datasets (e.g. for the relationship between flood damage and forested area, Bradshaw et al. 2007). The lack of studies on a global scale may be simply due to the lower frequency of global studies in the published literature. However, it is probably also related to the decision to exclude articles flagged as "review" during the initial literature search (because the focus was on original studies), though many review-type articles were not screened out by this process.

Results related to the linkages between natural capital and ecosystem services (see Section 3.3) were analysed to see if they varied depending on the location and spatial scale. The analysis was limited by the small number of database entries for the larger spatial scales and for certain continents, and results were therefore not conclusive. Full details are given in Annex 2.

3.2 Ecosystem type and condition

Around 94% of articles refer to specific ecosystems (the remainder being either general reviews, laboratory studies or experiments in artificial environments), with 35% studying multiple ecosystems (e.g. comparing woodland and grassland). Figure 8 shows that the most commonly studied ecosystems are terrestrial: woodland and forest (29% of all the ecosystems studied), followed by cropland (21%) and grassland (13%).

The least frequently cited ecosystems are those in marine environments, and sparsely vegetated land. This is partly a result of the choice of ecosystem services reviewed (e.g. the inclusion of freshwater fishing but exclusion of sea fishing). However it could also suggest that some ecosystems (e.g. sparsely vegetated land) are relatively unimportant for providing the selected ecosystem services, or that they have been poorly represented in the existing literature (this may be the case for marine ecosystems, see Liquete et al., 2013).

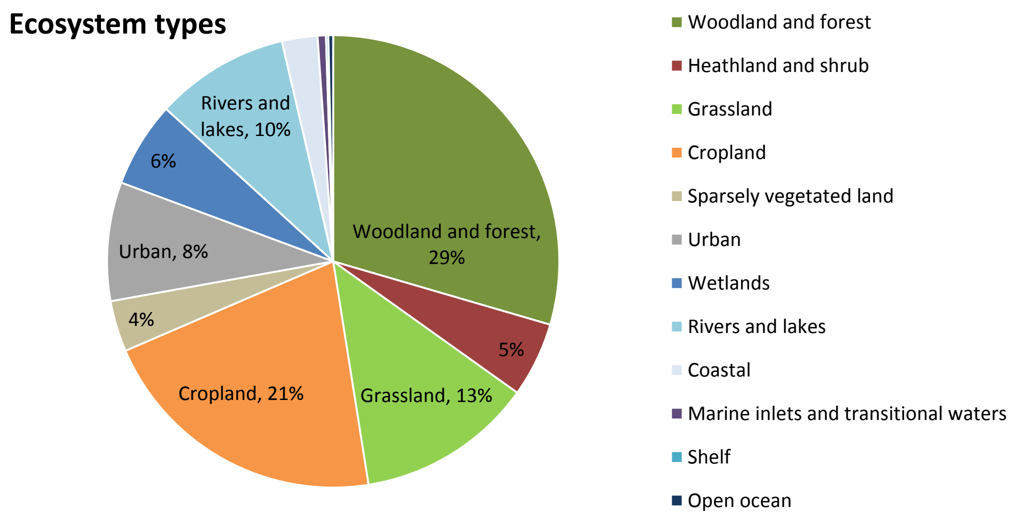

Figure 8: Types of ecosystems studied in the literature reviewed (% of total ecosystems mentioned). Note that a study can refer to more than one ecosystem.

Figure 9 shows the split of ecosystem types by ecosystem service. It is interesting that most of the regulating and cultural services studied cover a wide variety of ecosystems, especially for aesthetic landscapes, recreation and water quality regulation, whereas some provisioning services tend to focus on one dominant ecosystem. There are obvious associations: food production, pollination and pest regulation studies focus on cropland; freshwater fishing studies focus mainly on rivers and lakes; timber production studies refer only to forests; and air quality studies tend to focus on urban trees (often classified as both urban and woodland). The importance of forests is clear: they feature in all 13 categories of ecosystem services, and are the main focus in studies of water supply, atmospheric regulation (carbon storage) and water flow regulation (flood prevention). Wetlands feature strongly in studies of water flow and water quality regulation, and coastal environments are important for species-based recreation, including eco-tourism (e.g. whale and dolphin watching) and recreational fishing.

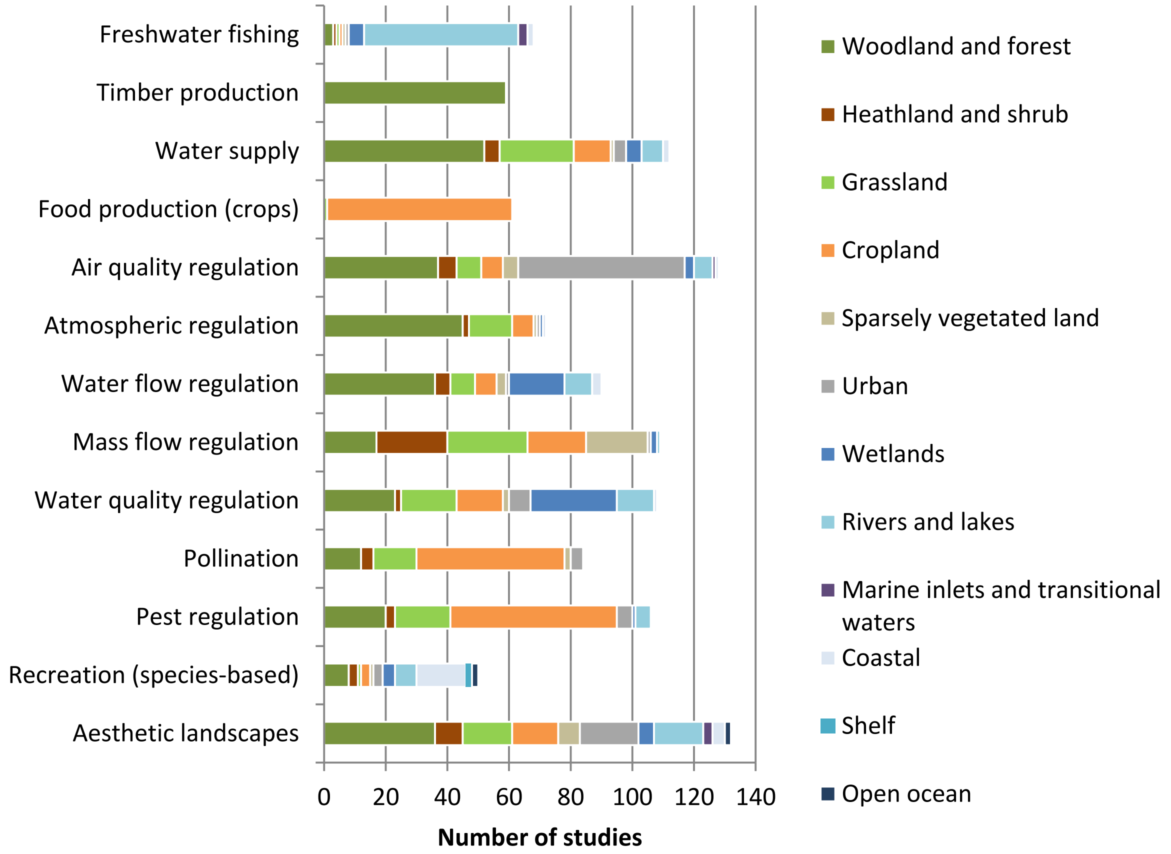

Figure 9: Types of ecosystems studied in the literature reviewed, by ecosystem service. Note that a study can refer to more than one ecosystem.

It is not possible to quantitatively analyse whether the contribution of biotic attributes to the ecosystem service varies by ecosystem, because, for studies where multiple ecosystems are described, attributes were not recorded separately for each ecosystem. Timber production is the only service where no articles reviewed refer to multiple ecosystems, but in this case (unsurprisingly) "woodland and forest" is the only ecosystem discussed and so cross-comparison is not possible. However, detailed information on the contribution of different biotic attributes for each ecosystem is recorded in the comments within the database, and this information has been used to perform a qualitative comparison as part of Section 3.3.2 on biotic attributes.

Information on ecosystem condition is limited, being present in only 25% of the articles reviewed. In fact, information on condition is rarely stated explicitly in the articles, but it can sometimes be inferred, for example if the area is described as being protected, or if the article states that forests have been degraded through logging. It should be noted that this information was recorded to aid interpretation of the impact of ecosystem condition on ecosystem services, and not to evaluate ecosystem conditions in general: that would require a more extensive review. However, some trends can be seen. Food production is associated in most cases with cropland (for obvious reasons), which appears to be in a worsening condition, with 12 articles out of 60 citing an unfavourable and declining condition due to factors related to over-exploitation, such as soil erosion or lack of water availability, compared to only 4 articles implying a favourable condition. The negative impact of agricultural activities on the condition of other ecosystems, mainly wetlands (due to conversion for agriculture or pollution from fertilisers), is also noted in several studies.

The condition of rivers/lakes used for freshwater fishing also appears to be predominantly declining, with 15 articles citing unfavourable conditions and only 6 citing favourable conditions.

3.3 Linkages between natural capital and ecosystem services

This section analyses the links between natural capital and the delivery of ecosystem services. Natural capital is defined as the biotic and abiotic components of nature that directly or indirectly produce value for people. Biotic components include plants, animals, fungi, bacteria and dead organic material; abiotic components include water, air, minerals and rock. These components, and the interactions between them, provide ecosystem services. In addition, the condition of the natural capital and the delivery of the services are influenced by abiotic factors such as temperature, wind, evaporation rate, slope and nutrient supply.

In this section we first describe the range of ecosystem service providers identified in the review, which are the species populations, functional groups, communities or habitats (with the latter including both biotic and abiotic components) that contribute to providing a service. We then analyse the contribution of biotic attributes to ecosystem service provision – not just the contribution of individual biotic components such as particular species of plants and animals, but also the diversity of species, and specific characteristics such as species size, community age and animal behaviour. Next we look at the influence of abiotic factors on service delivery. Finally, we combine all components to analyse the direction and strength of evidence linking natural capital with ecosystem services using network diagrams to show the links between ecosystem service providers, biotic attributes and abiotic factors in an operational classification.

3.3.1 Ecosystem Service Providers (ESPs)

The most common ESP is the entire community or habitat, which features in 46% of the studies reviewed (Figure 10). Most of these studies focus on a single community or habitat, though 14% cover multiple habitats – typically comparing a variety of habitats such as woodland and grassland, or primary forest and secondary forest. Specific species populations are the next most commonly cited ESP, accounting for 36% of the articles reviewed, with over half of these studying multiple species. Functional groups (single and multiple) receive less attention, accounting for only 16% of the articles reviewed, although evidence for the importance of functional groups is growing in more recent literature.

It should be noted that Figure 10 does not indicate the relative overall importance of different ESPs, as the ESP is partly a function of the scientific method chosen to investigate the ecosystem service (i.e. whether the researchers choose to investigate the role of one or more species, functional groups or entire communities). Also, the ESP is rarely explicitly identified as such in the journal articles, because much of the literature does not specifically investigate ecosystem services. More often, the ESP was inferred by the reviewer from the information given in the article.

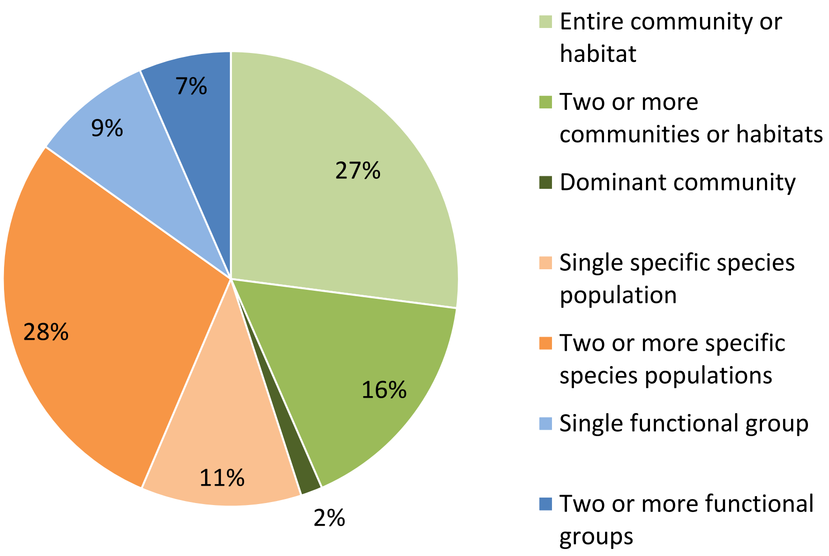

Figure 10: A breakdown of the Ecosystem Service Providers (ESPs) studied in the reviewed literature (% of studies).

The ESPs for each ecosystem service are shown in Figure 11. It is immediately obvious that for studies investigating provision of food, fish and timber, the ESP is generally two or more specific species, with many studies comparing the performance of different food crops, fish or tree species. In contrast, studies on water supply focus predominantly on comparisons of two or more habitats, e.g. forest and grassland.

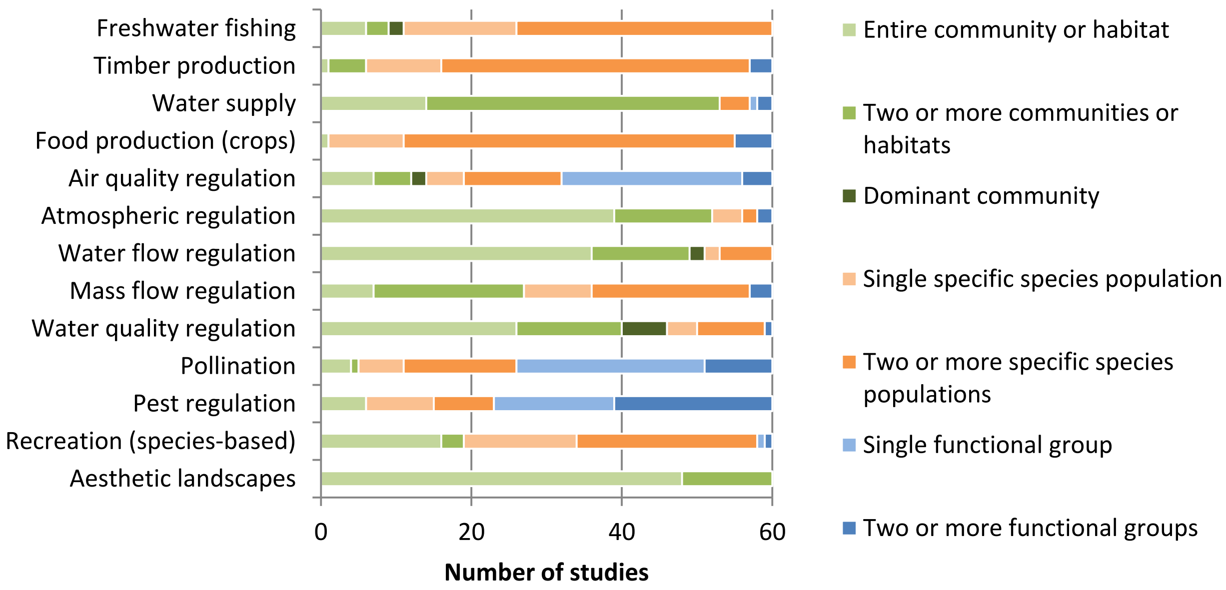

Figure 11: Number of studies showing a linkage between a specific ESP and ecosystem service.

For the regulation and maintenance services, pollination and pest regulation are typically provided by one or more functional groups (such as wasps, bees or pest predators in general), whereas for atmospheric, mass flow, water flow and water quality regulation the ESP is predominantly a single habitat such as a forest. For air quality regulation, the ESP is generally categorised as one or more functional groups, e.g.

urban trees and/or shrubs, or urban vegetation in general. For cultural services, species-based recreation is (unsurprisingly) dominated by studies of one or more specific species, whereas for aesthetic landscapes the ESP is always one or more entire habitats.

3.3.2 Biotic attributes of natural capital contributing to ecosystem services

The literature review found that the selected ecosystem services are influenced by a wide range of biotic attributes (Figure 12). The most commonly cited attribute is community/habitat area (37% of studies). This reflects the large number of studies where the most important attribute is simply the size of the area of the ecosystem, such as lakes for fishing, forests for controlling flood risk, wetlands for purifying water, tree cover for improving air quality, natural habitats for encouraging pest predators, or flower meadows for supporting pollinating insects. Habitat type and structure are also important, being the 3rd and 4th most commonly cited attributes (each cited in 31% of studies). 'Structure' covers a number of different physical variables, not all of which can be assigned a "direction of impact", but it was most commonly interpreted as structural diversity. This is important in a number of different ways: more diverse habitats provide better food and shelter for pollinating insects and pest predators; structural diversity enhances the aesthetic appeal of landscapes; and structural complexity tends to improve water flow, water quality and atmospheric regulation.

The second most cited attribute was the presence of a particular species (in 34% of studies), with species abundance being mentioned in 17% of studies. As mentioned above, many of these studies compared the performance of different species in delivering a service. Species size and weight was the most commonly cited species-specific attribute, being mentioned in 13% of studies. The presence and abundance of specific functional groups (such as 'trees' or 'pollinators') were the focus of 21% and 11% of studies respectively.

The fifth most cited attribute is a classic measure of biodiversity: species richness (30% of studies). This is capable of enhancing ecosystem services in two ways: through the 'selection effect', where the presence of a greater number of species increases the chances that some of them will be good providers of a particular ecosystem service, and through the 'niche complementarity' effect, where a mix of species with different characteristics enables greater use of the available resources. The review identifies several examples of niche complementarity, such as greater carbon storage in forests with a range of tree and shrub canopy heights and root depths. Functional diversity and functional richness are investigated less often, but are found to be important in 9% and 6% of cases, respectively.

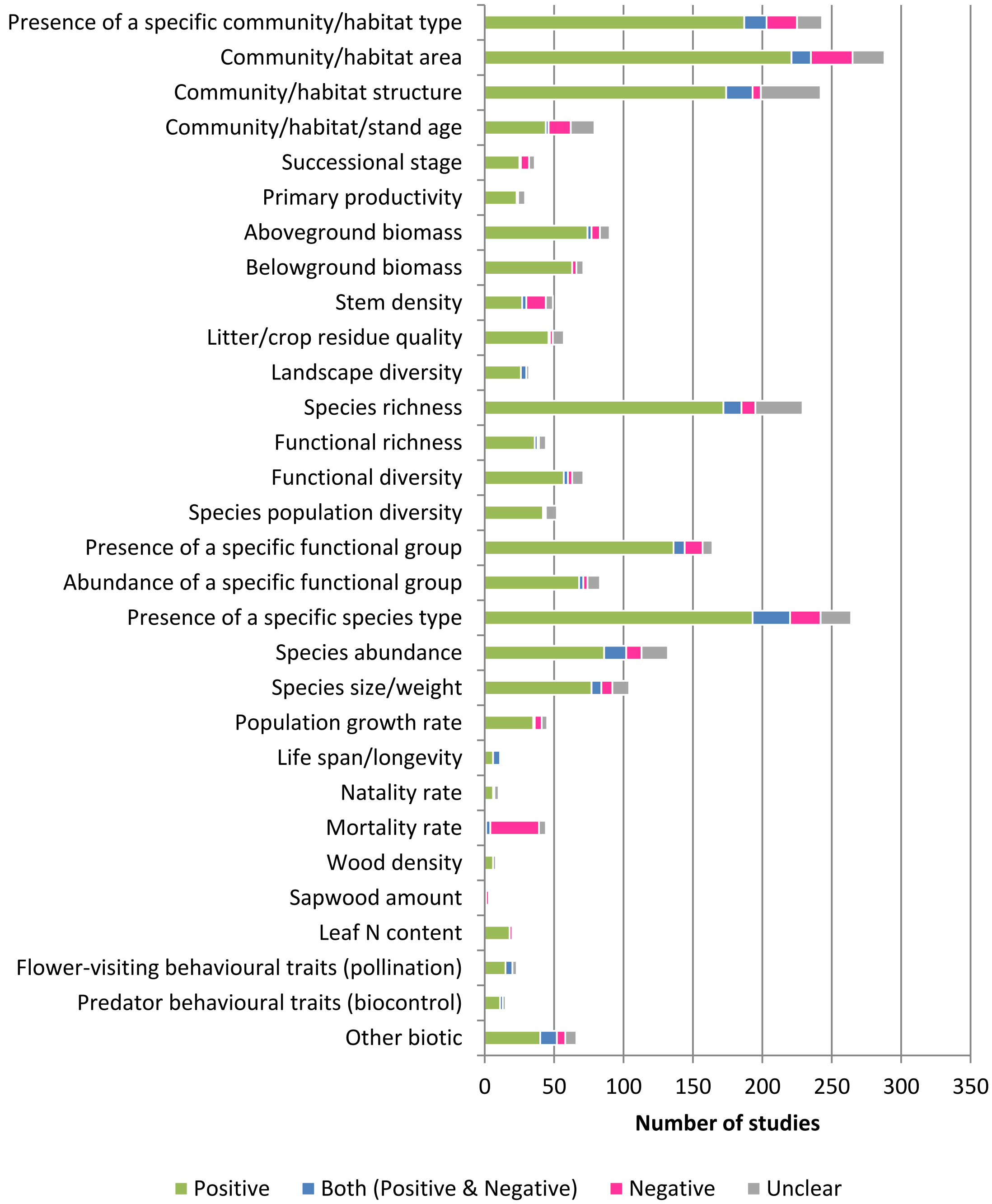

Figure 12: Frequency and direction of links between biotic attributes and ecosystem services.

Additional biotic attributes, not included in the original list, are identified in 9% of studies and are categorised as "Other biotic". These include a very wide variety of attributes, such as species evenness, leaf-area index (important for air quality regulation) and root density.

In most cases (73%), biotic attributes are found to improve ecosystem services provision, with 7% of studies citing both positive and negative impacts and 11% being unclear. However, in 9% of cases there is a negative influence, particularly (for obvious reasons) for mortality rate.

Table 4 shows how the biotic attributes vary between ecosystem services. This table groups the attributes into three categories broadly related to:

- the community or habitat;
- biological or physical diversity; and
- characteristics of a specific species or functional group.

The table shows the number of papers that cite a link between an ecosystem service and a specific biotic attribute, including positive, negative , mixed (both positive and negative) and unclear links, with links cited by a greater number of papers shown in darker shades of grey. Table 5 shows only positive links, with links cited by a greater number of papers shown in darker shades of green, and Table 6 shows only negative links (ignoring studies that show mixed or unclear links), with links cited by a greater number of papers shown in darker shades of red.

The importance of community/habitat type, area and structure is clear from the high number of links in the first three columns of all these tables, especially for the regulation and maintenance services, but also for water supply and aesthetic landscapes. Other habitat traits are also important for certain services. Atmospheric regulation shows a strong dependence on above- and below-ground biomass (as this is directly correlated with carbon storage), and also with community/stand age and successional stage, because older forests tend to have larger trees and thus store more carbon. Community/stand age is also important for the services of water flow regulation, water quality regulation and water supply, though for freshwater supply 12 studies show a negative link with the service and only two links are positive.

Many services show a strong dependence on the abundance of particular species, especially, as expected, species-based recreation, but also the provisioning services of food, fishing and timber where species need particular characteristics such as palatability (for food crops and fish) or straight growth habits (for timber). For some services, specific functional groups are important: these include groups of pollinators and pest predators such as bees and wasps, as mentioned previously, but also, for the services of air quality and mass flow regulation, functional groups of plants such as large vs small leaved trees or deep vs shallow rooted shrubs. For fishing, and to a lesser extent species-based recreation, the size or weight of species is also important.

The table also shows the importance of species richness for a wide range of services, especially for timber production where 87% of articles report a link: this includes 35 articles showing a positive link, usually where polycultures or mixed forests were more productive than monocultures, and five with a negative link, typically where competition from other species reduced the productivity of commercial timber species. Species richness is also cited as being important for enhancing food production: 73% of articles report a link, with only one of these being negative. Both of these effects are mainly due to niche complementarity, with mixtures of species of different heights or root depths making better use of the available light, water or nutrient resources.

The negative links shown in Table 6 are mainly concentrated in the column for mortality rate, and the row for water supply — both highlighted between red lines on the table. Forest plantations can reduce available water through interception of rainfall and transpiration, so that forest area, age and stem density may all have a negative impact on water supply. For the other services, there are some examples of negative impacts arising from the abundance of certain non-native species such as commercial honeybees which

compete with native bees, introduced fish which predate native fish, or invasive vegetation which chokes rivers and increases flood risk. The five cases where species abundance was negatively linked to the service of species-based recreation refer to the value placed on rare species by nature-watchers.

For air quality regulation, the “other biotic” attributes cited in 26 studies mainly refer to leaf area index, which is critical for air quality regulation but which was not included in the pre-defined database list.

Table 4: Number of studies showing a link (positive, negative, mixed or unclear) between an ecosystem service and a specific biotic attribute. Higher numbers highlighted in darker shades of grey. 60 papers were reviewed for each service.

	Community / habitat										Diversity					Specific species or functional group														
	Presence of a specific community/habitat	Community/habitat area	Community/habitat structure	Community/habitat/stand age	Successional stage	Primary productivity	Aboveground biomass	Belowground biomass	Stem density	Litter/crop residue quality	Landscape diversity	Species richness	Functional richness	Functional diversity	Species population diversity	Presence of a specific functional group	Abundance of a specific functional group	Presence of a specific species type	Species abundance	Species size/weight	Population growth rate	Life span/longevity	Natality rate	Mortality rate	Wood density	Sapwood amount	Leaf N content	Flower-visiting behavioural traits	Predator behavioural traits (biocontrol)	Other biotic
Freshwater fishing	13	17	13		1	8	3			2	5	15	1	1	4	4	2	21	31	27	7	2	3	17			1			
Timber production	2		9	3	4	1	2		12	4		52	7	11		10	1	24	10	4	3	1		2		1	7			
Water supply	30	38	8	21	1	1	2	5	10	2		3			1	8	1	17		3	5					3				6
Food production (crops)	2	4	2				11	9		11	1	44	4	5	14	27	10	23	1	3	8			1			10			
Air quality regulation	6	29	10	3		2	7		2		1	6	2	2	4	14	4	24	3	10		1		2						26
Atmospheric regulation	13	17	19	22	8	10	38	27	6	9		20	2	13	6	8	8	22	4	13	9	4	1	10	8		1			3
Water flow regulation	6	53	22	13	3		1	2	1	4						5	4	6	4	5	1									1
Mass flow regulation	37	31	35	6	14	1	13	23	8	15		9	3	8		24	1	26	2	7	7									1
Water quality regulation	43	40	14	8	2	4	6	5	4	4	1	8	1	3	4	7	5	22	7	9	2						1			
Pollination	25	20	30						1		10	28	11	14	7	33	23	22	27	3			1					23		9
Pest regulation	32	27	33	1	2	2	6		3	6	7	14	11	9	1	15	19	5	16	5	3	5	3	5			1		15	10
Recreation (species-based)	4	3										20	2	3	11	7	5	45	24	12			2	5						6
Aesthetic landscapes	30	9	47	2	1		1		2		7	10		2		2		7	3	3				2						4

Table 5: Number of studies showing a positive link (not including mixed or unclear) between an ecosystem service and a specific biotic attribute. Higher numbers highlighted in darker shades of green. 60 papers were reviewed for each service.

	Community / habitat										Diversity					Specific species or functional group														
	Presence of a specific community/habitat	Community/habitat area	Community/habitat structure	Community/habitat/stand age	Successional stage	Primary productivity	Aboveground biomass	Belowground biomass	Stem density	Litter/crop residue quality	Landscape diversity	Species richness	Functional richness	Functional diversity	Species population diversity	Presence of a specific functional group	Abundance of a specific functional group	Presence of a specific species type	Species abundance	Species size/weight	Population growth rate	Life span/longevity	Natality rate	Mortality rate	Wood density	Sapwood amount	Leaf N content	Flower-visiting behavioural traits	Predator behavioural traits (biocontrol)	Other biotic
Freshwater fishing	12	12	10		1	6	1			2	5	8	1	1	4	4	2	16	17	21	6	1	2	1			1			
Timber production	1		7	2	1	1	2		7	3		35	5	9		6		18	7	4	2					1	6			
Water supply	8	7	5	2	1			2	1	1		1			1	2		1		1										1
Food production (crops)	1	4	2				11	8		10	1	35	4	5	11	23	9	19		1	7						10			
Air quality regulation	5	27	4	1		2	5		1			4	1	1	1	12	3	15	2	9		1								18
Atmospheric regulation	12	17	14	18	8	9	35	25	2	6		16	2	8	5	6	8	15	4	12	8	2			6		1			1
Water flow regulation	5	41	21	10	2		1	2		2						4	3	3	1	3	1									1
Mass flow regulation	34	31	28	5	8	1	11	21	8	14		7	3	7		22		20	1	3	7									1
Water quality regulation	40	37	8	3	1	3	5	5	4	3		6	1	3	2	7	4	17	6	6	1									
Pollination	22	15	19						1		8	25	10	11	7	32	21	17	20	3								15		4
Pest regulation	17	20	22	1	2	1	2		1	5	5	9	8	7	1	10	13	4	11	1	3	2	2						11	5
Recreation (species-based)	4	3										18	1	3	10	7	5	43	15	10			2							6
Aesthetic landscapes	26	7	34	2	1		1		2		7	8		2		1		5	2	3										3

Table 6: Number of studies showing a negative link (not including mixed or unclear) between an ecosystem service and a specific biotic attribute. Higher numbers highlighted in darker shades of red. 60 papers were reviewed for each service. Red lines highlight that most negative impacts are related to mortality rate and potable water supply.

	Community/ habitat										Diversity					Specific species or functional group														
	Presence of a specific community/habitat	Community/habitat area	Community/habitat structure	Community/habitat/stand age	Successional stage	Primary productivity	Aboveground biomass	Belowground biomass	Stem density	Litter/crop residue quality	Landscape diversity	Species richness	Functional richness	Functional diversity	Species population diversity	Presence of a specific functional group	Abundance of a specific functional group	Presence of a specific species type	Species abundance	Species size/weight	Population growth rate	Life span/longevity	Natality rate	Mortality rate	Wood density	Sapwood amount	Leaf N content	Flower-visiting behavioural traits	Predator behavioural traits (biocontrol)	Other biotic
Freshwater fishing												1						1		1				14						
Timber production			1		3				4			5	1	2		3	1							2						
Water supply	20	26		12			2	2	9	1						5	1	10		2	5					2				1
Food production (crops)								1				1				1		2						1						
Air quality regulation							1									1								2						3
Atmospheric regulation			1				2					1		1				2				1		8						1
Water flow regulation	1	3		1					1							1		1	3	1										
Mass flow regulation	1		1	1	2											2		2		2										
Water quality regulation				2	1					1							1	1		2							1			
Pollination		1																2	2											
Pest regulation			2				1																	2			1			1
Recreation (species-based)												2			1				5					5						
Aesthetic landscapes			1															1	1					1						

3.3.3 Abiotic factors affecting ecosystem service provision

The literature search focused on biotic attributes, but we also recorded the impact of any abiotic factors that were mentioned in the articles. It should be noted that the intention was to record the way in which abiotic factors affect the ability of the ecosystem to provide the service, and not simply the direct impact of the abiotic factor, such as the increased risk of flooding due to heavy rain. A range of abiotic factors are found to influence ecosystem service provision, with precipitation, soil and temperature being the most frequently cited, but with mixed positive and negative impacts (Figure 13). For example, heavy precipitation may reduce the ability of ecosystems to provide flood protection if the ground becomes saturated, but lack of precipitation may lead to forest dieback which will reduce provision of many services. Note that for soil, geology and 'other' it was not meaningful to record the direction of impact so these impacts are all shown as 'unclear'.

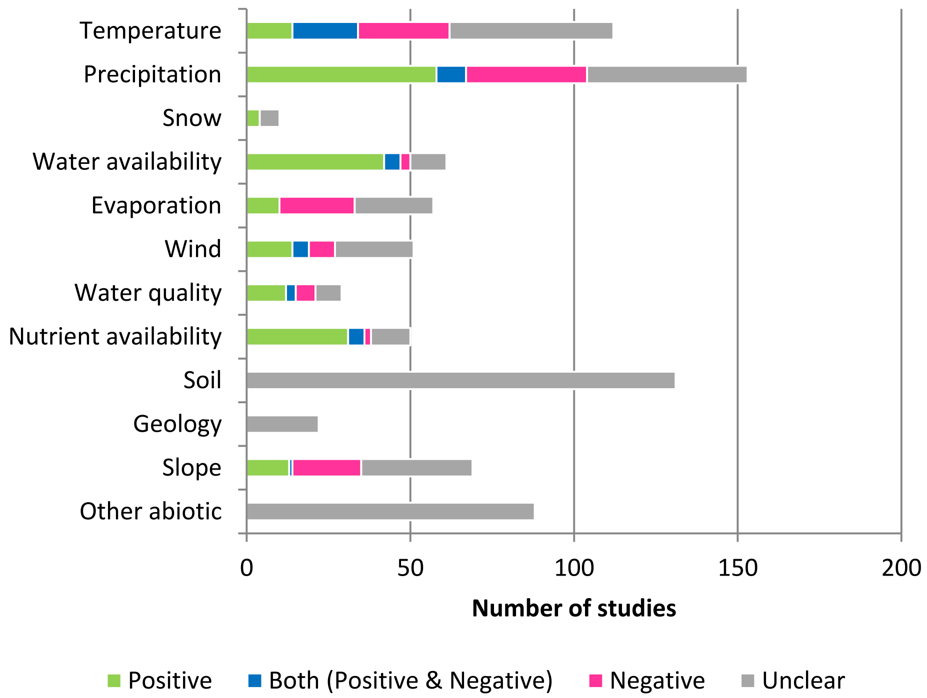

Figure 13: Frequency and direction of linkages between abiotic factors and the 13 ecosystem services reviewed.

There is considerable variation between ecosystem services (Figure 14; Table 7 to Table 9). Water supply appears to be particularly highly influenced by abiotic factors, with soil, precipitation and evaporation mentioned in over 70% of journal articles. Table 8 shows the strong positive impact of precipitation and Table 9 shows the negative impact of evaporation (specifically, evapotranspiration by trees). Food production is also dependent on a range of abiotic factors including nutrient availability, soil, and precipitation. Table 8 shows how a number of services depend on water availability for establishment and survival of vegetation, and also shows the positive impact of water availability (rivers and lakes) on aesthetic landscapes. Table 9 also shows the adverse impact of precipitation and slope on water flow and mass flow regulation, and the adverse impact of temperature on air quality regulation. In contrast, pest

regulation, species-based recreation and aesthetic landscapes seem to be influenced by a much smaller range of abiotic factors.

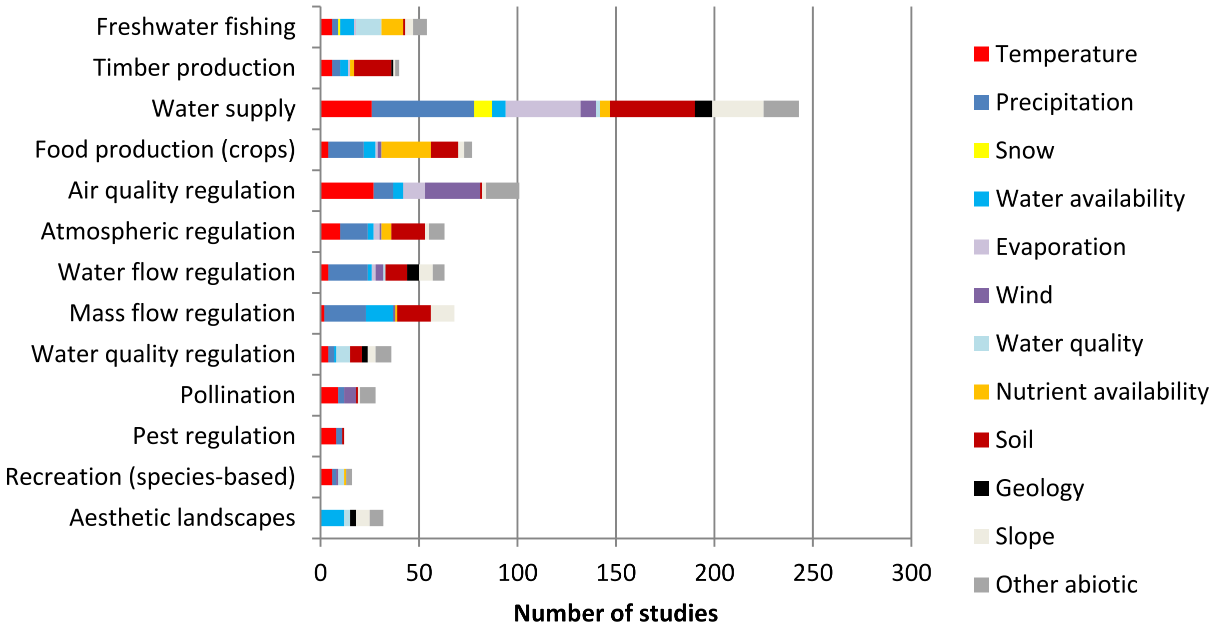

Figure 14: The importance of abiotic factors in the literature reviewed for each ecosystem service.

Table 7: Percentage of studies showing a linkage between a specific abiotic factor and ecosystem service. Greatest percentages are highlighted in darker shades of grey.

	Temperature	Precipitation	Snow	Water availability	Evaporation	Wind	Water quality	Nutrient availability	Soil	Geology	Slope	Other
Freshwater fishing	6	3	1	7	1		13	11	1		4	7
Timber production	6	4		4	1			2	19	1	1	2
Water supply)	26	52	9	7	38	8	2	5	43	9	26	18
Food production (crops)	4	18		6	1	2		25	14		3	4
Air quality regulation	27	10		5	11	28			1		2	17
Atmospheric regulation	10	14		3	3	1		5	17		2	8
Water flow regulation	4	20		2	2	4	1		11	6	7	6
Mass flow regulation	2	21		14		1		1	17		12	
Water quality regulation	4	3		1			7		6	3	4	8
Pollination	9	3				6			1		1	8
Pest regulation	8	3							1			
Recreation (species-based)	6	2				1	3	1				3
Aesthetic landscapes				12			3			3	7	7

Table 8: Percentage of studies showing a positive linkage between a specific abiotic factor and ecosystem service. Greatest percentages are highlighted in darker shades of green.

	Temperature	Precipitation	Snow	Water availability	Evaporation	Wind	Water quality	Nutrient availability	Soil	Geology	Slope	Other
Freshwater fishing		2	1	6			6	5			2	
Timber production	4	2		1	1			1	9		1	1
Water supply)		33	3	3			1		1			1
Food production (crops)	1	6		5				21	4			
Air quality regulation	3	4		3	7	13					1	3
Atmospheric regulation	1	5		3		1		3	1			1
Water flow regulation	1	1			2		1		5	2	1	1
Mass flow regulation	2	3		10				1	3		1	
Water quality regulation	1			1					2		1	2
Pollination		2										2
Pest regulation	1											
Recreation (species-based)							1					
Aesthetic landscapes				10			3			2	6	5

Table 9: Percentage of studies showing a negative linkage between a specific abiotic factor and ecosystem service. Greatest percentages are highlighted in darker shades of red.

	Temperature	Precipitation	Snow	Water availability	Evaporation	Wind	Water quality	Nutrient availability	Soil	Geology	Slope	Other abiotic
Freshwater fishing	3				1		3	1			2	3
Timber production				2					3			1
Water supply					21	1						1
Food production (crops)	1	5			1	1			3		3	
Air quality regulation	11	1				1					1	6
Atmospheric regulation	3	2							2		1	4
Water flow regulation	3	14		1		3			2		5	4
Mass flow regulation		13				1			5		8	
Water quality regulation	3	2					2			1		1
Pollination	1											1
Pest regulation	2											
Recreation (species-based)	1					1	1	1				1
Aesthetic landscapes											1	1

3.3.4 Network diagrams showing the links between natural capital and ecosystem services

The network diagrams summarise the typology (classification scheme) that we have developed to describe the relationships between different components of natural capital and ecosystem services. For each service, they show the main ecosystem service providers and the way in which biotic attributes and abiotic factors contribute to (or detract from) provision of the service. As described in section 2.4, the colour of the links corresponds to the direction of the interaction (positive, negative or neutral/unclear), and the thickness of the lines represents the strength of the evidence for the links (based on the percentage of studies supporting the link).

The diagrams, which are presented and described fully in section 4, highlight the degree of complexity in the interactions between natural capital and ecosystem service provision. The provision of most of the regulation and maintenance services appears to be quite complex, with studies demonstrating the influence of a large spread of biotic and abiotic attributes. Figure 15 shows one example, for the service of atmospheric regulation. In contrast, the attributes influencing some of the cultural and provisioning services, especially the service of aesthetic landscapes, appear to be simpler (Figure 16).

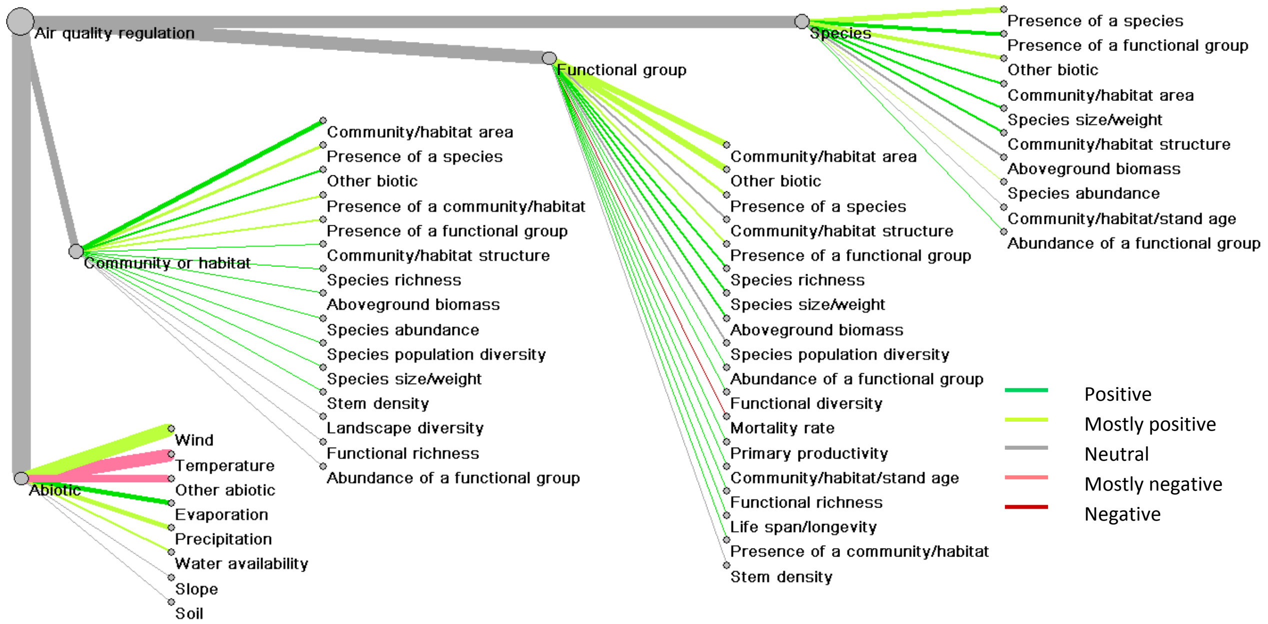

Figure 15: Network of links to ESPs, biotic attributes and abiotic factors for the service of atmospheric regulation. Line thickness indicates the number of studies showing a given link.

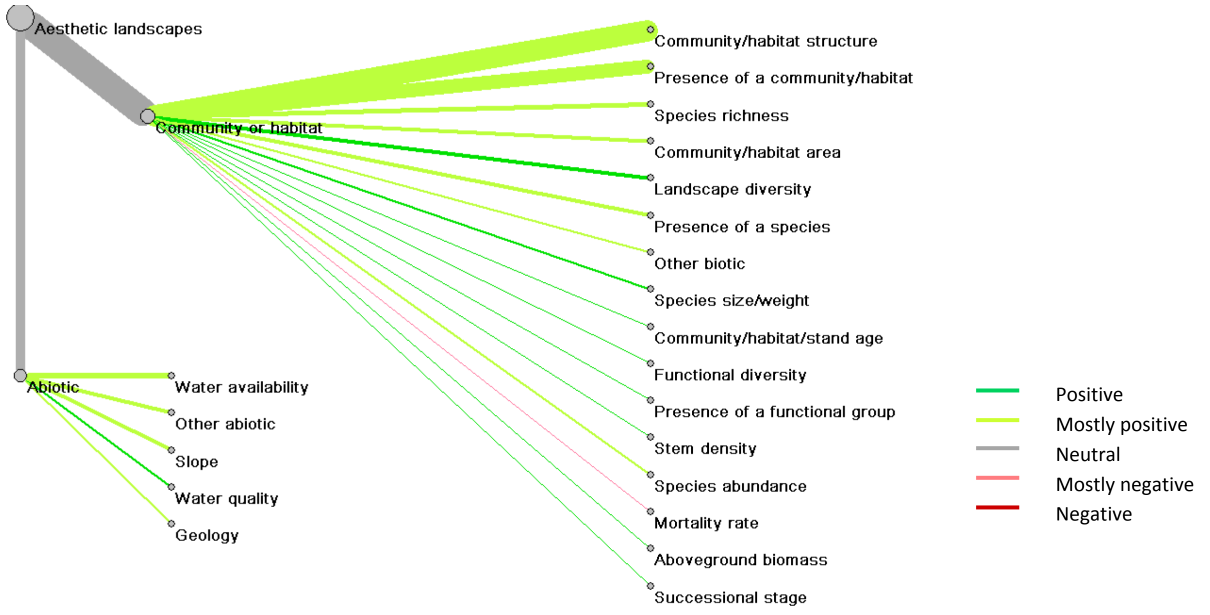

Figure 16: Network of links to ESPs, biotic attributes and abiotic factors for the service of aesthetic landscapes. Line thickness indicates the number of studies showing a given link.

As discussed in sections 3.3.2 and 3.3.3 above, the diagrams illustrate that biotic attributes tend to enhance ecosystem service provision, shown by the dominance of green lines for biotic attributes, whereas the effect of abiotic factors is variable, depending very much on the ecosystem service and study concerned.

3.4 Human input and management

Two thirds of the journal articles reviewed mention some form of human management or human impact on the ecosystem service. This covers a wide range of activities: intensive crop production; extensive grazing; management of timber plantations; management of nature reserves and fishing lakes; planting of trees to improve air quality, or grass to stabilise soil; provision of suitable habitat for pest predators and pollinators; and loss or damage to ecosystems through development. Slightly more studies mention positive impacts (21%) than negative impacts (15%) , with a large number (18%) recording both together (Figure 17).

Although 52% of studies concern direct input to the ecosystem, there are also examples of indirect effects, where human influence on surrounding areas affects provision of the service. This is most common for the services of water supply (where land use in the catchment affects water supply) and pollination (due to the presence or absence of habitats for pollinators near to crops) (Figure 18).

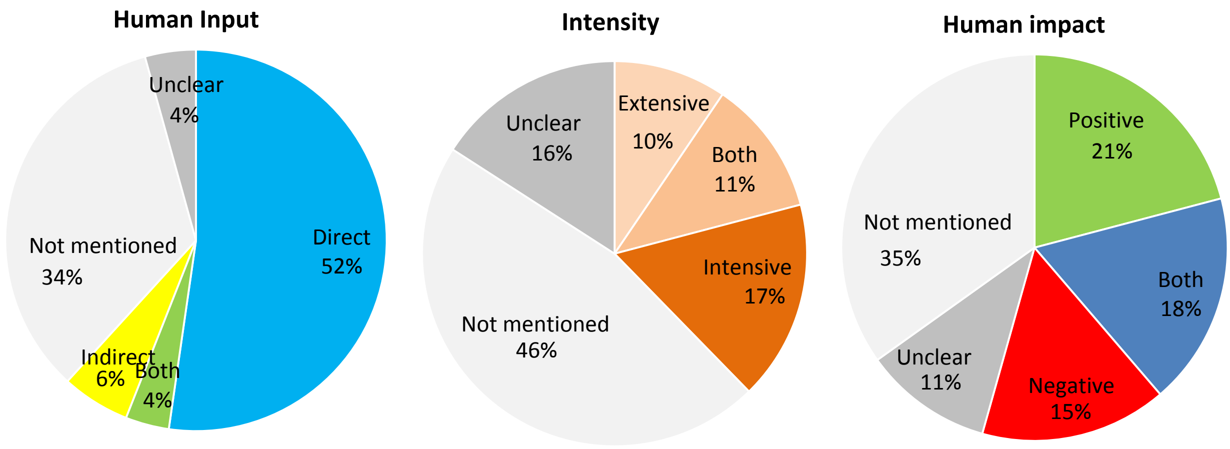

Figure 17: Percentage of studies showing different types of human input and management, management intensity and impact for all ecosystem services reviewed.

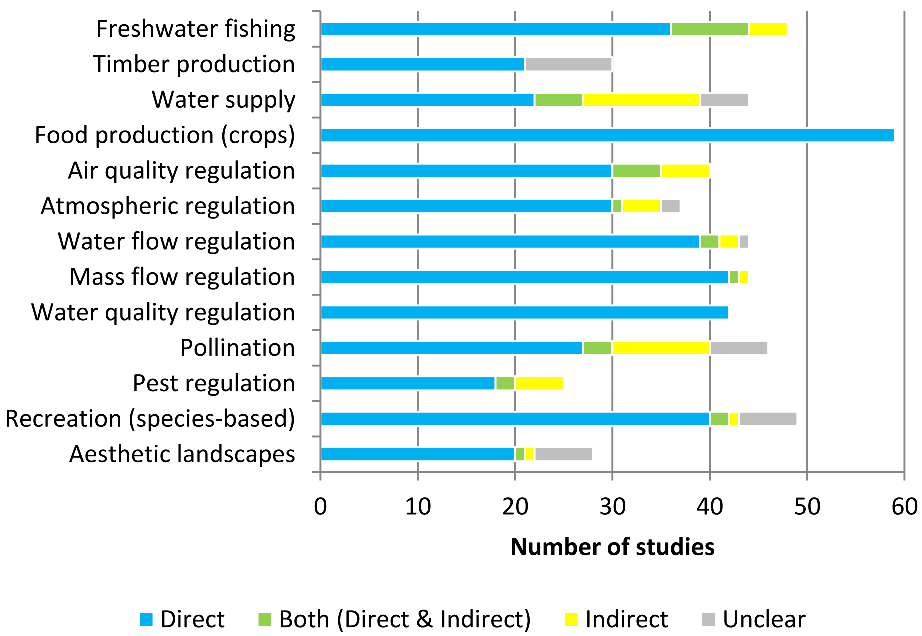

Figure 18: Number of studies showing direct or indirect human input and management for each ecosystem service reviewed.

Figure 19 illustrates the split between intensive and extensive inputs. Food and timber production and freshwater fishing are dominated by intensive forms of management, including fertilisation and fish stocking programs, though a number of studies also look at extensive cultivation or compare intensive and extensive methods. Water quality regulation is also dominated by the impacts of intensive practices such as deforestation (negative) or wetland construction (positive), and articles on mass flow regulation often refer to the negative impacts of intensive cultivation. In contrast, the majority of articles on air quality regulation refer to input as both intensive and extensive. For example, the practice of planting trees in urban areas is extensive, but also intensive due to their subsequent irrigation needs (Jim and Chen, 2008); whereas the construction of green roofs in Chicago could be intensive, extensive or semi-intensive depending on which type was planted (Yang et al., 2008).

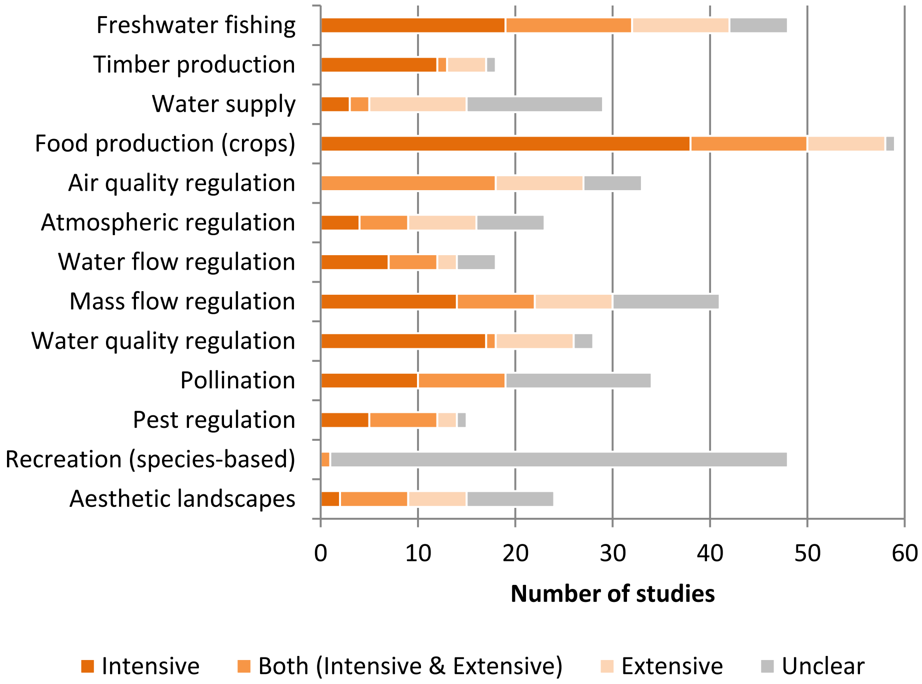

Figure 19: Number of studies showing extensive or intensive human input and management for each ecosystem service reviewed.

Figure 20 shows the split of impacts due to human input and management by ecosystem service. Most services record a mix of positive and negative impacts, and often both together. This reflects a typical pattern observed in many articles that record damage to ecosystem services from unsustainable development, such as loss of carbon storage due to clear-felling of forests, together with positive impacts from beneficial interventions such as reforestation or designation of protected areas. Another common approach is for articles to compare two alternative forms of management with positive and negative impacts, such as the impact on pollinators or pest predators of intensive agriculture vs. organic agriculture.

For food crop and timber production, the service would not exist without some level of human input, so no studies cite purely negative impacts. However there are many studies with mixed positive and negative impacts, providing interesting examples of the conflicts and trade-offs often encountered between and within ecosystem services. Intensive cultivation can increase yields in the short term but can have adverse impacts (such as over-extraction of groundwater for irrigation or loss of soil through erosion) that could decrease production in the longer term.

Air quality regulation is another example of a service where all the studies reviewed were classified as having some level of positive human impact, e.g. through planting and maintaining urban trees, or protecting forests from development. However, there could also be negative impacts from the removal of urban trees due to development.

It is also interesting to compare the services of species-based recreation and aesthetic landscapes. For recreation, a large number of positive impacts are recorded which consist largely of conservation actions to protect wildlife and encourage eco-tourism. However, a few negative impacts are also recorded where tourist behaviour or illegal hunting can deplete wildlife populations. For aesthetic landscapes, more of the

studies recorded negative impacts because in most cases people express a preference for unmanaged landscapes. However, some studies find that human elements such as cultural buildings or traditional farming can enhance landscapes, and some user groups such as farmers and certain ethnic groups prefer managed landscapes.

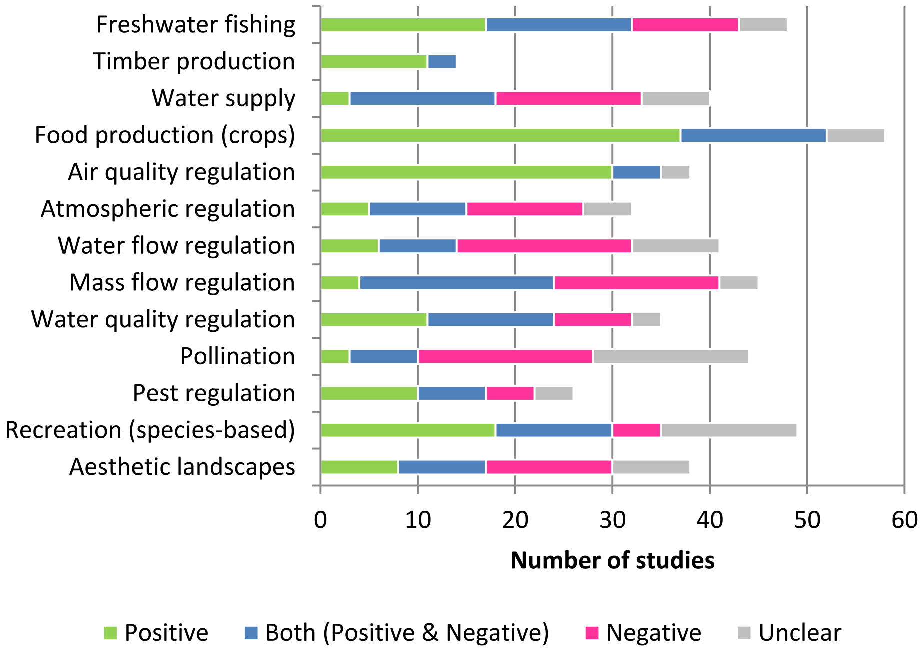

Figure 20: Impact (direction) of human input and management for each ecosystem service reviewed.

3.5 Interactions with other ecosystem services

Interactions between different ecosystem services were mentioned in 46% of articles, though they were not often investigated explicitly. The majority of interactions (64%) identified between ecosystem services were documented as being positive, with an additional 8% citing both positive and negative interactions (Figure 21).

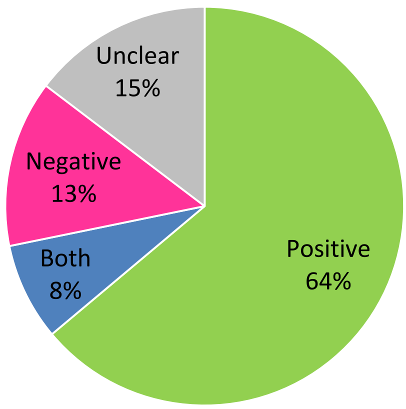

Figure 21. Direction of interactions between ecosystem services in the literature reviewed

Interactions between different ecosystem services are shown in Table 10. The most frequent interaction cited in the literature reviewed, with 33 counts, is that between mass flow and water flow regulation. Most of the other frequently cited interactions (>20 counts) occur between the regulating and provisioning services, for example between timber production and atmospheric regulation (23 counts); water flow regulation and water supply (29 counts); and food production and pollination (24 counts). There are also 21 interactions between water supply and timber supply. Few specific interactions were identified between the two cultural services, though species-rich landscapes were appreciated by both services, and crowding (which could be seen as "too much" recreation) was cited as a negative impact for aesthetic landscapes.

Table 10: The number of studies mentioning interactions between ecosystem services. Most frequent interactions are highlighted in darker shades of grey. Green indicates provisioning services; blue indicates regulation and maintenance services; and red indicates cultural services.

	Freshwater fishing	Timber production	Water supply	Food production (crops)	Air quality regulation	Atmospheric regulation	Water flow regulation	Mass flow regulation	Water quality regulation	Pollination	Pest regulation	Recreation (species-based)	Aesthetic landscapes
Freshwater fishing													
Timber production	3												
Water supply	3	21											
Food production (crops)	7	3	10										
Air quality regulation	1	3	4	1									
Atmospheric regulation	1	23	23	19	18								
Water flow regulation	9	14	29	13	15	10							
Mass flow regulation	3	3	11	25	6	13	33						
Water quality regulation	10	7	9	16	2	9	18	17					
Pollination		1	2	24		1	2	1	1				
Pest regulation		3		22	1	3	2		2	10			
Recreation (species-based)	18		2	3	7	2	8	2	5	2	6		
Aesthetic landscapes	3	8	1	8	18	5	12	3	2			3	
Other	5	4	12	7	24	12	12	11	7		4	2	3

Positive interactions (including "both positive and negative") are shown in Table 11, and are most common between different regulating services. The greatest number of positive links (25) is between mass flow and water flow regulation, as both services are provided by measures such as afforestation, with less runoff and erosion occurring in vegetated areas. There are also strong positive links (24) between food production and pollination, as many crops (e.g. fruit, cacao, oilseed and coffee) are clearly dependent on pollination, and between food production and pest regulation (20 links). Food production is also linked to mass flow regulation, as farming methods that reduce soil erosion can increase crop yields. There is a strong synergy between water quality and water flow regulation (17 links), both of which are typically enhanced by

wetlands, forests and other vegetation. Finally, planting trees to improve air quality also provides many benefits to other services: atmospheric regulation, water flow regulation and aesthetic landscapes. The large number of positive interactions (21) for air quality regulation under the “other” category refers mainly to the benefits of urban trees and green roofs for microclimate regulation.

Table 11: The number of studies mentioning positive interactions between ecosystem services. Includes studies citing “both positive and negative interactions”. Most commonly occurring positive interactions have been highlighted in darker shades of green. Green indicates provisioning services; blue indicates regulation and maintenance services; and red indicates cultural services.

	Freshwater fishing	Timber production	Water supply	Food production (crops)	Air quality regulation	Atmospheric regulation	Water flow regulation	Mass flow regulation	Water quality regulation	Pollination	Pest regulation	Recreation (species-based)	Aesthetic landscapes
Freshwater fishing													
Timber production	1												
Water supply	2	3											
Food production (crops)	5	3	7										
Air quality regulation	1	3	4	1									
Atmospheric regulation	1	11	9	11	17								
Water flow regulation	4	7	14	7	15	7							
Mass flow regulation	2	3	8	20	6	12	25						
Water quality regulation	8	3	4	12	2	2	17	17					
Pollination			1	24			1	1	1				
Pest regulation		2		20		1	2		2	7			
Recreation (species-based)	16		1	2	7	2	7	2	4	2	6		
Aesthetic landscapes	3	1		4	18	4	10	3	2			3	
Other	4	4	3	6	24	6	9	7	7		3	2	1

Negative interactions between ecosystem services are cited in only 13% of studies, plus the 8% that cite both positive and negative interactions. Table 12 shows that most of these antagonistic interactions occur between provisioning and regulating services, particularly for food and timber provision. Articles on water flow regulation and atmospheric regulation, for example, often mention the negative impact of deforestation driven by conversion of forest to farmland, or clear-felling of forest for timber. Food production also adversely affects mass flow regulation, as cultivation makes land more vulnerable to soil erosion, and fertiliser run-off can decrease water quality. Similarly, the literature on atmospheric regulation often cites a negative interaction with timber production, as regular harvesting of timber reduces carbon storage.

However, there are also major negative interactions between two provisioning services: timber production and water supply. Timber plantations can be very intensive users of limited water supplies in areas where water is scarce. In other examples, conversion of land for timber production competes with cloud forest habitats which are beneficial to water supplies (Hamilton, 1995); and the change from broad-leaved forest to coniferous plantation causes reductions in water yield (Komatsu et al., 2008).

Table 12: The number of studies mentioning negative interactions between ecosystem services. Includes studies citing "both positive and negative interactions". Most commonly occurring negative interactions have been highlighted in darker shades of red. Green indicates provisioning services; blue indicates regulation and maintenance services; and red indicates cultural services.

	Freshwater fishing	Timber production	Water supply	Food production (crops)	Air quality regulation	Atmospheric regulation	Water flow regulation	Mass flow regulation	Water quality regulation	Pollination	Pest regulation	Recreation (species-based)	Aesthetic landscapes
Freshwater fishing													
Timber production	2												
Water supply	2	13											
Food production (crops)	5		2										
Air quality regulation													
Atmospheric regulation		10	5	10									
Water flow regulation	5	7	6	8		2							
Mass flow regulation			1	8									
Water quality regulation	2	4		5		4	2						
Pollination		1	1				1						
Pest regulation		1		7	1					3			
Recreation (species-based)	4			3			1		1		1		
Aesthetic landscapes				5			2						
Other	1		1	1	1	2	5	3	2		1		

There are some interesting examples of trade-offs amongst the 8% of interactions with both positive and negative effects. For example, Bisseleua et al. (2013) find that a higher shade index increases beneficial predators and reduces pest populations, but it also reduces cocoa yield.

3.6 Thresholds

In total only 78 instances of thresholds were identified in the main literature review. This includes safe minimum standards (15) and legal boundaries (4), mainly cited for air quality regulation, but the majority

are categorised as biophysical thresholds, with 32 being attached to specific ecosystem service indicators, and the remaining 27 being classed as "other biophysical thresholds". These are often unique thresholds for each study where changes in behaviour were observed, such as the percentage of vegetation or forest cover that can safely be removed before a decrease in water flow regulation (flood protection) occurs. Thresholds may also correspond to a classification scheme, e.g. habitats classified as either high existing value or marginal existing value (Jackson et al., 2013).

Figure 22 highlights that studies related to air and water quality regulation, water supply and mass flow regulation cite thresholds most frequently. In contrast, none of the articles discussing aesthetic landscapes or timber production indicate the existence of any thresholds.

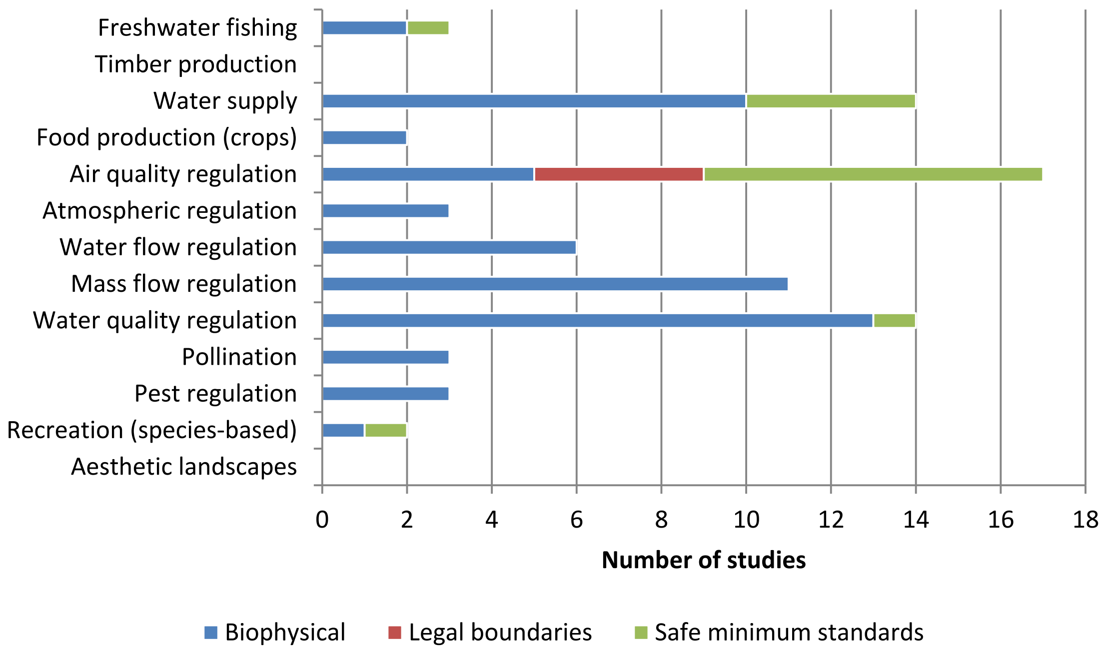

Figure 22: The frequency of thresholds discussed in the literature for the 13 ecosystem services.

A wide range of thresholds for water supply were identified, including the level of deforestation in the Amazon after which significant changes in cloud cover are predicted (Nosetto et al., 2005); the amount of rainfall required before recharge occurs (Petheram et al., 2002), and two studies describing thresholds for the reduction of runoff due to afforestation (e.g. Farley et al., 2005). In contrast, for water flow regulation, several studies note that the attenuation of peak stream flow starts to decline after the removal of 20-30% of forest cover in the catchment area (e.g. Bathurst et al., 2011; Lin and Wei, 2008). Some studies on water flow regulation found that the service declined for larger flood events (e.g. the presence of salt marsh vegetation was found to have little effect on flood attenuation above an inundation depth of 1.3m, Möller et al., 2007; forest cover has no effect for extreme events, e.g. Bruijnzeel, 2004; Moore and Wondzell, 2005). However, Green & Alila (2012) dispute this view (see report on water flow regulation in Annex 5).

Thresholds for water quality regulation include the minimum level of richness, evenness and diversity required in a microbial community for denitrification (Martin et al., 1999); a saturation effect between species richness and ecosystem functioning (Cardinale et al., 2011); a threshold for chronic sediment delivery to streams (Rashin et al., 2006); and a biomass threshold for seagrass (Moore, 2004). For

atmospheric regulation, it was found that although carbon storage increases with species richness, it can saturate at a low number of species, with storage increasing at a slower rate thereafter (Chen, 2006).

Air quality regulation thresholds included safe minimum standards and legal boundaries for pollutants including ozone, particulate matter, nitrous oxides and carbon monoxide. Examples included international programs (WHO standards), national programs (the US Ambient Air Quality Standard), and local standards (e.g. the California Ambient Air Quality Standard).

Other examples include a biophysical threshold for pollination describing the point when bee visits no longer increase pollination (Greenleaf and Kremen, 2006). Finally, a study concerning recreational angling identified a noise threshold from boats after which fish stress was exhibited (Lewin et al., 2006).

As the main literature review did not specifically search for the word “threshold”, a supplementary review was carried out (see Annex 1 for details). This identified only 28 original journal articles that attempted to quantify or otherwise assess biophysical thresholds that relate to ecosystem services. Of these, only around half provided a quantitative value for a threshold, and not all of these are related to a specific ecosystem service. Only one article was identified in both the main and supplementary literature reviews: the study by Letourneau et al. (2012), which found a steep decline in pest parasitism at thresholds of 38% or 51% crop cover (for two different species). Most of the other thresholds found in the supplementary review also related to land cover, including the impact of vegetation cover on soil productivity (Gao et al., 2011); the impact of removal of forest patches in Madagascar on pollination and seed dispersal (Bodin et al., 2006) and loss of tree cover in Australia on pest control (Fischer et al., 2010); the effect of landscape complexity in Argentina on a range of services including food production and water flow regulation (Laterra et al., 2012); the provision of pollinator habitat (Keitt, 2009); the impact of seagrass cover on fish habitat and atmospheric regulation (Wagner et al, 2012); and the impact of “biologically vital areas” on a range of regulating and cultural services (Szulczewska et al., 2014). However, there are also one or two examples of thresholds related to temperature and salinity, such as the impact of drought on oyster populations in estuaries (Petes et al., 2012) and the impact of water temperatures on trout (Wardynsky et al., 2013).

3.7 Indicators for ecosystem service assessment

The majority of the ecosystem service literature reviewed (88%) used assessment methods which were based on primary data, such as direct field observations or public statistical databases. Mechanistic, correlative and conceptual models were used very rarely.

The frequency of the different indicators used for each ecosystem service is presented in Annex 3. It is worth noting that the initial list of potential indicators, derived from the JRC review on indicators for mapping ecosystem services (Egoh et al., 2012), included a number of indicators that were never used or cited in the literature, and 36% of the studies reviewed used indicators that were not included in the JRC review. This information could be used to considerably improve the list of indicators for future work on ecosystem services. Full details, including the list of newly identified indicators, are given in Annex 3.

3.8 Policies

Only 105 of the 780 studies reviewed (13%) cite a particular policy. Some of these cite multiple policies, with 127 policies identified in total. Of the 24 EU policies included in the database, only seven are mentioned in the literature, and these are rarely cited (Table 13). However, policy is discussed more often than this implies, with many articles discussing policy recommendations in general terms. The 89 "Other" policies include local and national policies, and international policies outside the EU.

Table 13: Policies mentioned in the literature reviewed

Policy	Number of studies
Ambient Air Quality directive	4
Biodiversity Strategy	3
Common Agriculture Policy	9
Habitat Directive	7
Marine Strategy Framework Directive (MSFD)	1
Soil Thematic Strategy	2
Water Framework Directive (WFD)	12
Other	89
Grand Total	**127**

Policies are cited most frequently for water flow regulation (22 counts, 5 of which are the Water Framework Directive), followed by air quality regulation, atmospheric regulation, pollination, water supply and species-based recreation. Full details are given in Annex 4.

4 Results for each ecosystem service

In this section we use network diagrams to present a summary of the results for each of the 13 ecosystem services in terms of the operational classification scheme (typology) that we have developed. The network diagrams show the links between ecosystem service provider, biotic attributes and abiotic factors for each ecosystem service. We also briefly discuss interactions between services. Full results for each service are presented in Annex 5.

4.1 Freshwater fishing

Around a quarter of the studies on freshwater fishing focus on aquaculture ponds, many of which are in Asia, and another quarter cover rivers, lakes or reservoirs used for recreational fishing, many of which are in North America. The remaining articles cover commercial or subsistence fishing in natural or semi-natural lakes and rivers, as well as some wider reviews and laboratory studies. The main indicator used to measure the service is the weight of fish caught per unit area of the water body per day or year.

The main provider identified for the service of freshwater fishing is specific populations of commercially important fish species, such as carp, tilapia, salmon or trout, though 11 studies refer to the entire community or habitat, meaning the community of fish within a particular habitat such as a lake (Figure 23).

A wide range of biotic attributes are discussed for both classes of ESP. Species-level attributes are the most important, with species abundance (stocking rate), species size/weight and population growth rate all having a predominantly positive impact on freshwater fishing. Larger fish were preferred by fishermen, and were also found to produce larger yields due to their higher survival rate (Li, 1999). Mortality rate was the only biotic attribute found to have a purely negative impact. However, there was a trade-off between species abundance and yield, because over-stocking reduces fish size and eventually leads to increased mortality (e.g. Lorenzen, 1995). Species abundance of particular non-native species can also have a negative impact in a few cases due to predation: for example, sea lamprey (*Petromyzon marinus*) caused a large decrease in populations of commercially important fish in Lake Superior (Lawrie, 1978). Species richness was also found to have a positive influence, with a number of studies finding higher productivity and yield in polycultures compared to monocultures. Although the main focus was on species attributes, a number of papers emphasised the importance of the habitat, i.e. the lake or river, with primary productivity, community/habitat area and structure all being important.

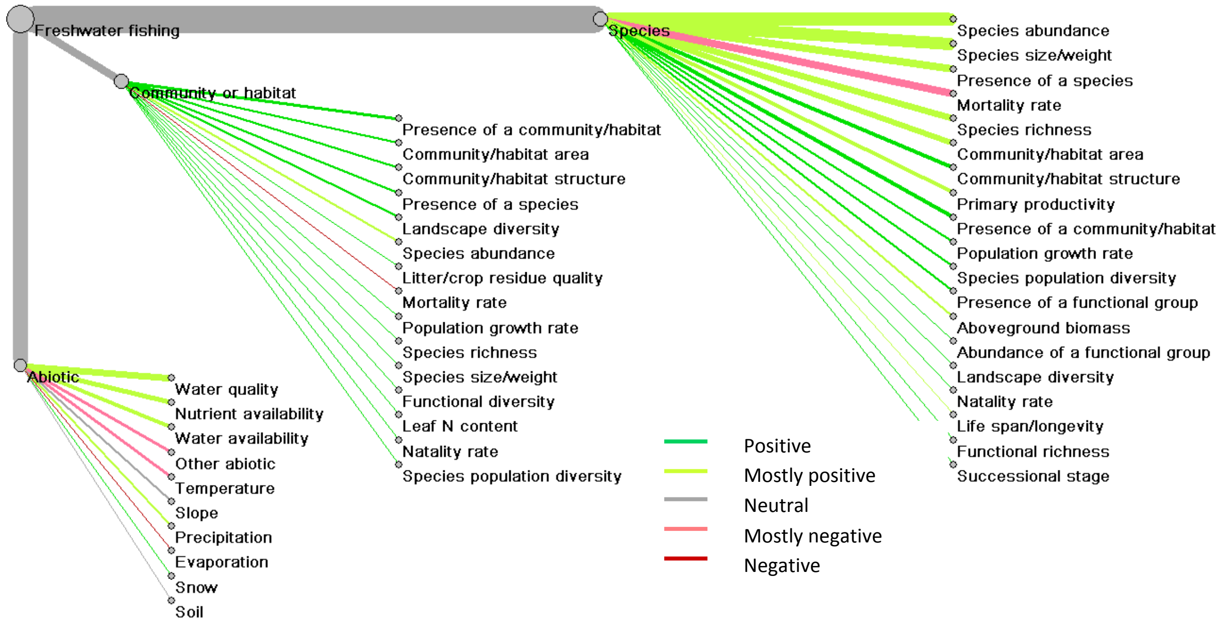

Figure 23: Network diagram showing linkages between ESPs, biotic attributes and abiotic factors for the service of freshwater fishing. Line thickness indicates the number of studies showing a given link.

A range of abiotic factors are discussed, of which water quality and nutrient availability are the most frequently cited. Nutrient availability has mixed impacts: it can improve fish production, e.g. through feeding fish in aquaculture ponds, but excess nutrients can also cause eutrophication.

Human management includes intensive activities such as stocking ponds, feeding and rearing fish, especially for the studies covering aquaculture. However, 25% of studies discuss more extensive management for recreational fisheries where fish feed mainly from natural sources. Management activities such as feeding and stocking, as expected, have a positive impact on fish catch (provided that overstocking is avoided). However, for natural fisheries, human activity can cause a negative impact due to over-fishing or habitat degradation. No specific thresholds were identified, though several articles mention that fish catch would be expected to decline above a certain stocking density.

Figure 24 shows the interactions with other ecosystem services that were identified in the freshwater fishing review (not including interactions with fishing that were identified in the other ecosystem service reviews). Not surprisingly, the main interaction is a positive link with species-based recreation, i.e. the sport of fishing. There are also some negative interactions with water flow regulation, as the construction of dams, drainage channels or irrigation systems can damage fish habitat and disrupt fish migration.

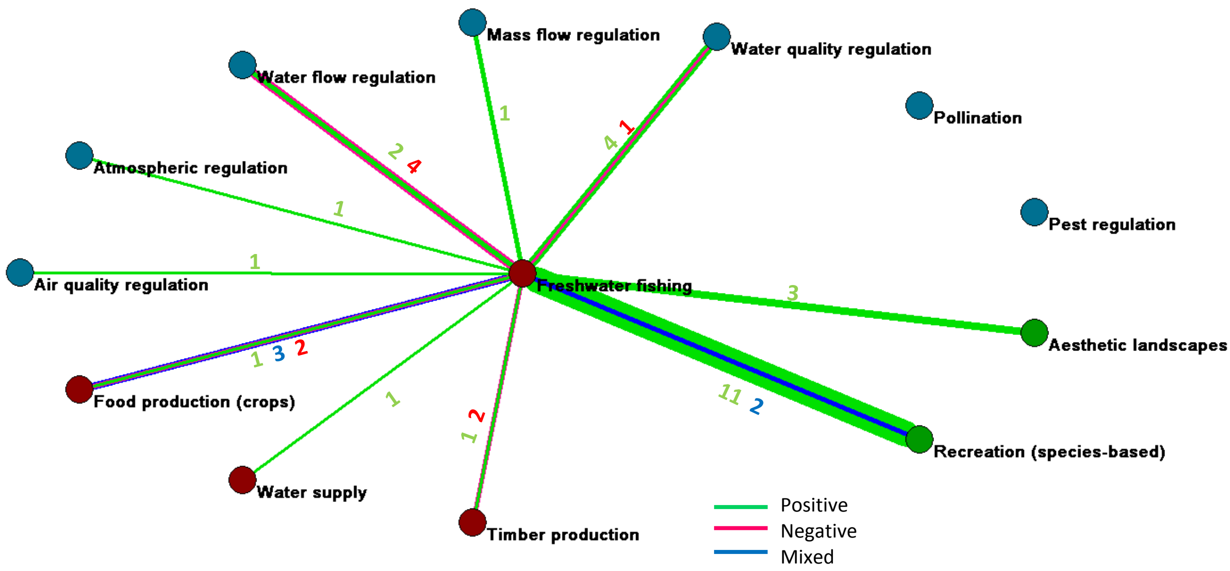

Figure 24: Interactions between freshwater fishing and other ecosystem services that were identified in the fishing review (unclear interactions and those identified in reviews of the other services are omitted). Line thickness is proportional to number of studies citing the interaction.

4.2 Timber production

The studies reviewed are split roughly equally between natural forests and timber plantations, and focus on forests containing commercially important species such as conifers and eucalyptus. There is a wide geographical spread, though the studies on plantations were located mainly in tropical regions. Timber production was measured using various indicators such as growth of the trees (height, diameter or circumference) or the production of wood (m^3 or tonnes).

The service of timber production is mainly provided by one or more specific species populations (e.g. Scots Pine and Silver Birch), although some studies are classified as dealing with functional groups (e.g. mixed conifer forest) (Figure 25).

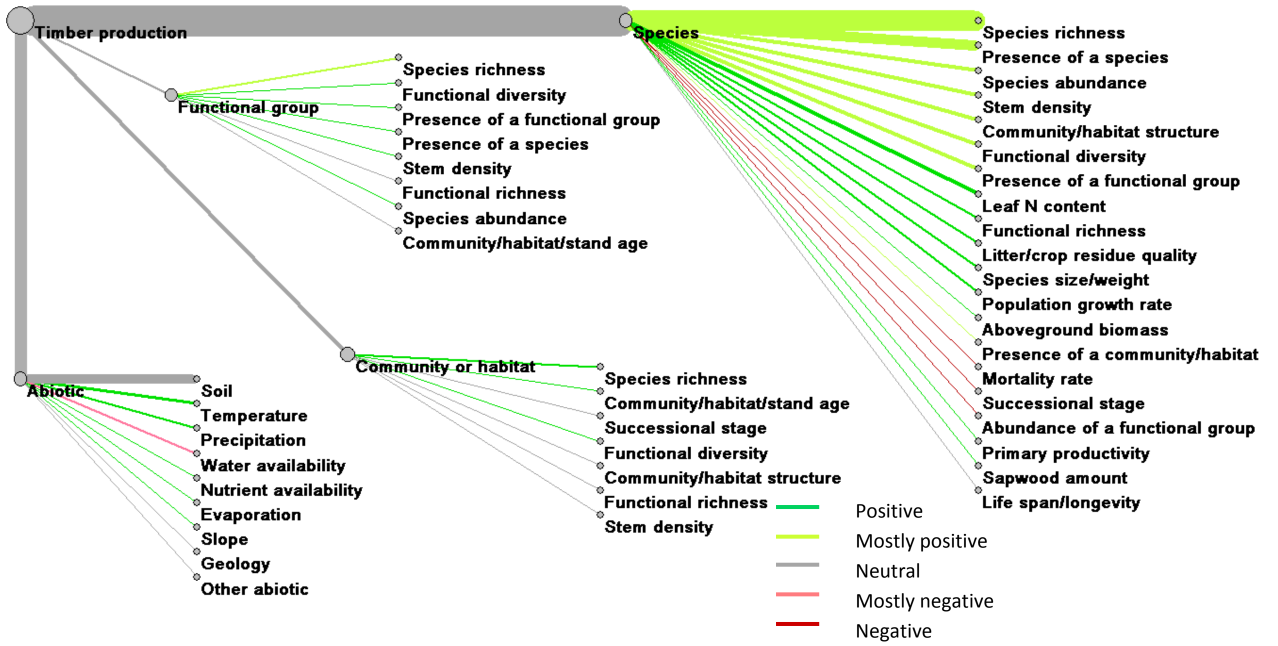

Figure 25: Network diagram showing linkages between ESPs, biotic attributes and abiotic factors for the service of timber production. Line thickness indicates the number of studies showing a given link.

The impact of biotic attributes seems to be predominantly positive, with species richness being cited the most often. Most studies (35) found evidence that plantation species are more productive in mixtures than in monocultures (e.g. Erskine et al., 2006), but there is some conflicting evidence, with five studies finding monocultures to be more productive (e.g. Nguyen et al., 2012). Other factors with a mainly positive impact on timber production include presence of a particular species (i.e. those with most commercial value), species abundance, stem density, functional diversity, and community/habitat structure. For example, Donoso et al. (2007) found that forests with mixed canopy heights are more productive due to better use of the available light. However there were some examples of negative impacts, including lower productivity at later successional stages (e.g. Vila et al., 2003), lower quality timber at higher stem densities due to overcrowding (e.g. Adame et al., 2014), and competition from functional groups such as understorey vegetation or tall trees with dense canopies that shade those beneath them.

For the abiotic factors, the most commonly mentioned is soil, though other factors such as precipitation and temperature are also found to have a positive impact in a small number of cases. Water availability sometimes had a negative impact due to waterlogging of the soil.

Perhaps surprisingly, few of the articles on timber production mention interactions with other ecosystem services (Figure 26). One or two articles mention the positive impact of trees on carbon storage, water flow and mass flow regulation, and the role of forests in providing habitat for pollinators and pest predators, with the direction of impact depending on the way in which the forests are managed. In contrast, articles on other ecosystem services mention numerous interactions with timber production, including both positive and negative interactions with atmospheric regulation and water flow regulation, and mainly negative interactions with water supply (see section 3.5).

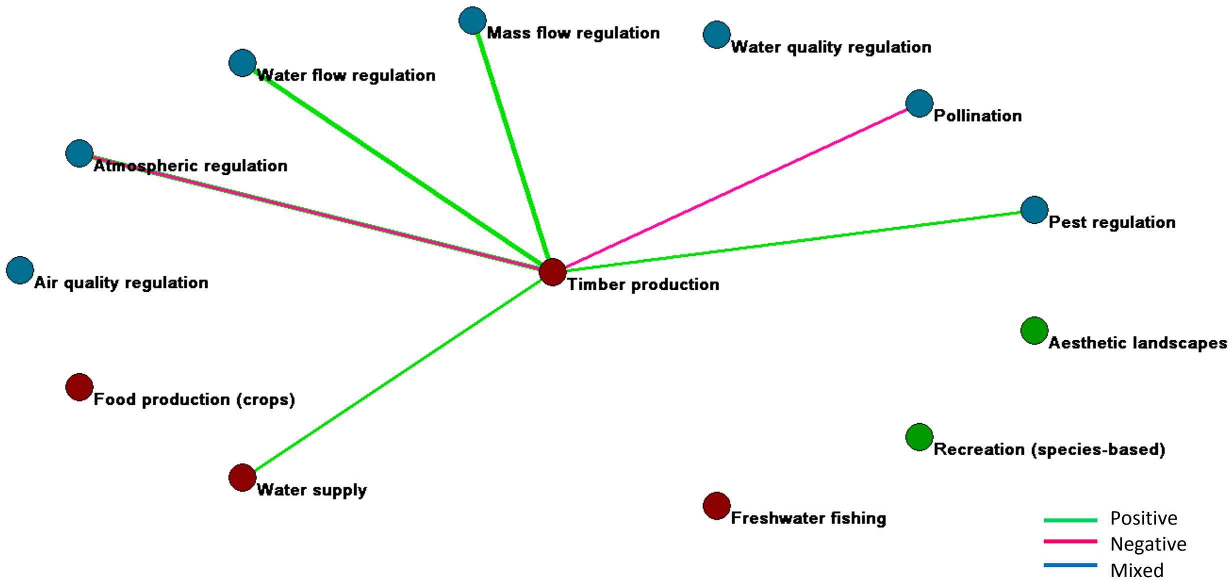

Figure 26: Interactions between timber production and other ecosystem services (unclear interactions and those identified in reviews of the other services are omitted). Line thickness is proportional to number of studies citing the interaction.

4.3 Water supply

There is little literature that explicitly investigates water supply as an ecosystem service; instead, the reviewer generally inferred the impact of natural capital from studies of the effect of land cover change in a catchment area (especially change in forest cover) on proxy indicators including stream flows, water levels or runoff. Because of this focus on land use studies, the ecosystem service provider is typically classified as the entire community or habitat, although some studies focus on specific species or functional groups (Figure 27). Studies mainly focus on areas where freshwater supply is limited or threatened, such as Australia and South Africa.

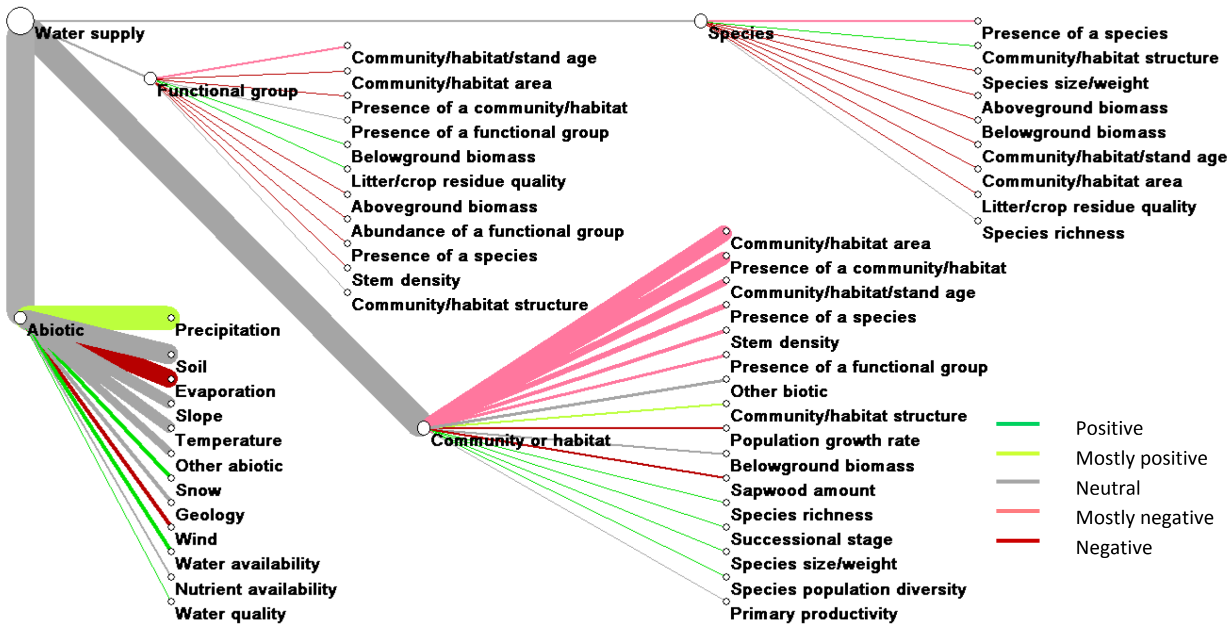

Figure 27: Network diagram showing the linkages between ESPs, biotic attributes and abiotic factors for the service of water supply. Line thickness indicates the number of studies showing a given link.

In contrast to the other ecosystem services, the impact of biotic attributes is often negative. Most (41) of the articles reviewed describe negative impacts from forests, as trees can intercept rainwater and absorb groundwater, thus reducing the supply available for humans downstream. The most commonly cited attributes with a negative impact are community/habitat area, presence of a community (forest), and stand age, as older/larger trees use more water (e.g. Nosetto et al., 2005). Similarly, higher stem density and higher sapwood area can increase water use (Kagawa et al., 2009), and harvesting and thinning are found to significantly increase runoff and therefore increase provision in many studies (e.g. Petheram et al., 2002; Sahin and Hall, 1996). There is a distinction between plantations and natural forests: many of the articles citing reduced water yield concerned plantations of species such as pine and eucalyptus, and some studies showed that water yield decreased when old growth forest was replaced with pine plantations (Rowe and Pearce, 1994; Komatsu, 2008). However 15 studies found beneficial impacts, with four showing how cloud forests intercept water from the air (e.g. Gomez-Peralta et al. 2005, Brauman et al. 2010) and several showing how forests, especially natural forests such as the old forest in the Western Ghats in India (Singh and Mishra, 2012), can increase water yield by improving infiltration and soil water storage capacity. However some of these studies found benefits for grassland compared to forest. Grasslands are also found to increase water provision compared to bare soil (Holdsworth and Mark, 1990).

Abiotic factors appear to have an important influence on this service, with precipitation and snow adding freshwater to the system, and hence improving provision, whereas evaporation (mainly evapo-transpiration by trees) leads to a loss of moisture and sometimes an increase of salt content in soils (e.g. Ruprecht and Stoneman, 1993) and thus reduces water supply. The direction for the remaining abiotic attributes, including temperature and slope, is unclear. Soil is often mentioned, for example in terms of porosity and soil moisture content. Buytaert et al. (2007), for example, find that soil compaction arising from forestry operations has a negative impact on water supply by reducing infiltration.

Human input clearly affects water supply, through land use management. As described above, the review found that afforestation can decrease freshwater supply, but that the choice of species is important: plantations of species such as pine and eucalyptus often cause a significant decrease in stream flow while native old growth forests can have a positive impact. Management techniques can also have an influence, with thinning of plantations increasing the water yield. Several studies found thresholds concerning the proportion of a catchment that could be forested before a reduction in water yield is observed, or the amount of rainfall necessary before surplus runoff is generated. However, the afforestation thresholds may be related to the difficulty of measuring small changes in stream flow rather than a true biophysical threshold.

Figure 28 shows that a number of interactions between water supply and other ecosystem services were identified, with the clearest being a negative interaction with timber production, due to the negative impact of plantations on water levels as discussed above. There are both positive and negative interactions with water flow regulation, as forests are generally beneficial for flood protection but often reduce water supply. The relationship with atmospheric regulation (carbon storage) is also a mix of positive and negative interactions reflecting the fact that some old growth forest and cloud forests can be beneficial for water supply, and that vegetated land can be better than bare soil for both these services. There are also links to water quality, as poor water quality reduces the supply of fresh water. In some cases native forests can enhance both these services, but in other cases forests can improve water quality but decrease water quantity as noted above.

The interactions with forest ecosystems are reflected in the coverage of policies in the literature, which mentions not only a number of national and local policies to improve water availability and quality, such as Integrated Water Resources Management and subsidies for water conservation, but also policies related to biodiversity and carbon storage in forests.

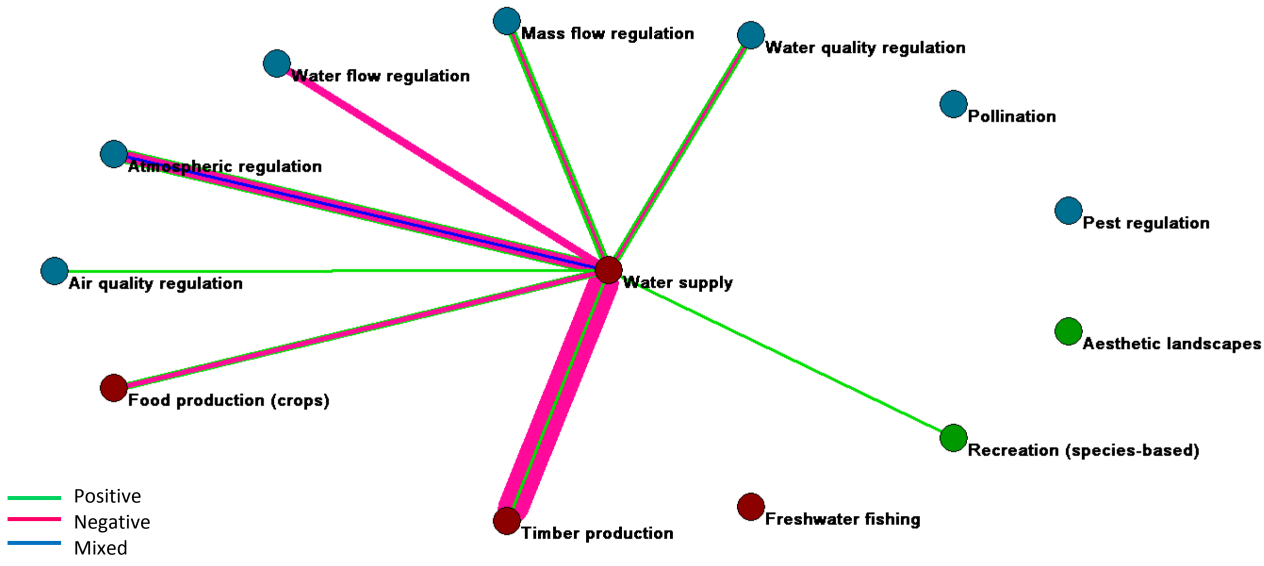

Figure 28: Interactions between water supply and other ecosystem services (unclear interactions and those identified in reviews of the other services are omitted). Line thickness is proportional to number of studies citing the interaction.

4.4 Food production (cultivated crops)

The studies reviewed on food production cover a wide geographical range, with 20 in Africa, 18 in North America, 14 in Europe and 11 in Asia. The most frequently cited indicator is 'crop yield', usually in tons/ha but sometimes in $/ha. The studies usually focus on one or more specific species populations, for example a mixture of crops, a single crop such as maize or wheat, or a mix of varieties of a single species (Figure 29), though several studies focus on functional groups (e.g. grains, legumes, tubers) and one addresses the entire agricultural landscape.

Species richness is the most frequently mentioned biotic attribute, as many of the studies look at sustainable agricultural techniques such as intercropping, crop rotation or the use of cover crops, all of which increase the number of crop species grown. The presence of particular functional groups or species is of course crucial, as only certain crops are palatable and suitable for cultivation, though this relationship is so obvious that it is not always explicitly mentioned in the literature. A number of studies explore the use of cultivar mixes, i.e. growing mixtures of several varieties of the same species (such as wheat), which is classed as species population diversity (genetic diversity). This often has a beneficial effect due to niche complementarity, e.g. when the different cultivars can access nutrients or water at different depths, and these mixtures are often more resistant to pests and diseases. However, sometimes a monoculture of the most productive species can be more successful, at least in the short term.

Aboveground and belowground biomass are clearly important as these are strongly related to crop yield for most crops, but the link to biomass was often too obvious to be explicitly mentioned. Litter / crop residue quality was also found to be important in a number of studies that looked at the impacts of mulching, especially with nitrogen-fixing legumes that can increase soil fertility as they decompose.

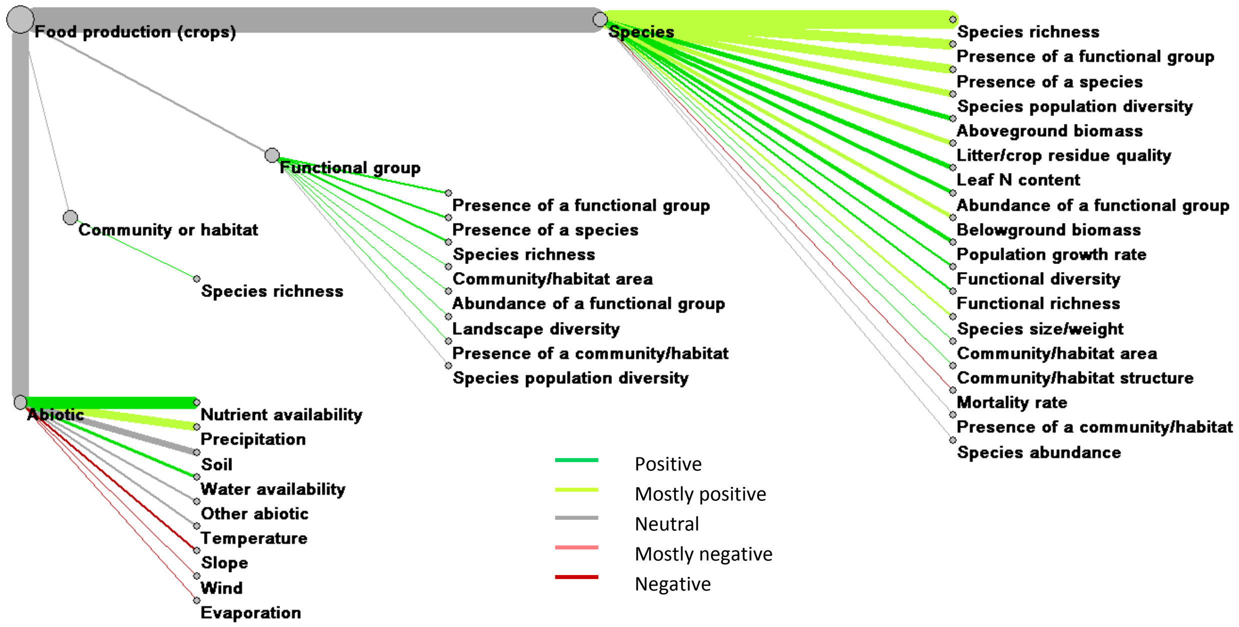

Figure 29: Network diagram showing the linkages between ESPs and abiotic factors for the service of food production (cultivated crops). Line thickness indicates the number of studies showing a given link.

Abiotic factors are frequently mentioned. Unsurprisingly, nutrient availability has a positive effect, with yields being increased by synthetic fertilisers and by more sustainable methods such as intercropping with legumes. Precipitation and water availability are also mainly beneficial, although heavy precipitation can wash away soil and nutrients, and waterlogged ground can cause problems in some contexts. Soil quality and temperature are also mentioned.

Direct human management is, by definition, present for all the studies on cultivated crops, and includes planting, drainage, irrigation, cultivation and application of fertilisers and pesticide. Management is generally classed as being intensive, i.e. the aim is explicitly to optimise the yield, although 8 studies involve extensive methods such as manual weeding or low-input agriculture, and 12 compare intensive and extensive methods. Impacts are generally positive in that the crops would not grow without the human intervention, but several studies also reported negative impacts typically due to over-cultivation leading to soil erosion or depletion of soil fertility.

The complexity of these impacts is reflected in the wide range of interactions between food production and other ecosystem services, as shown in Figure 30.

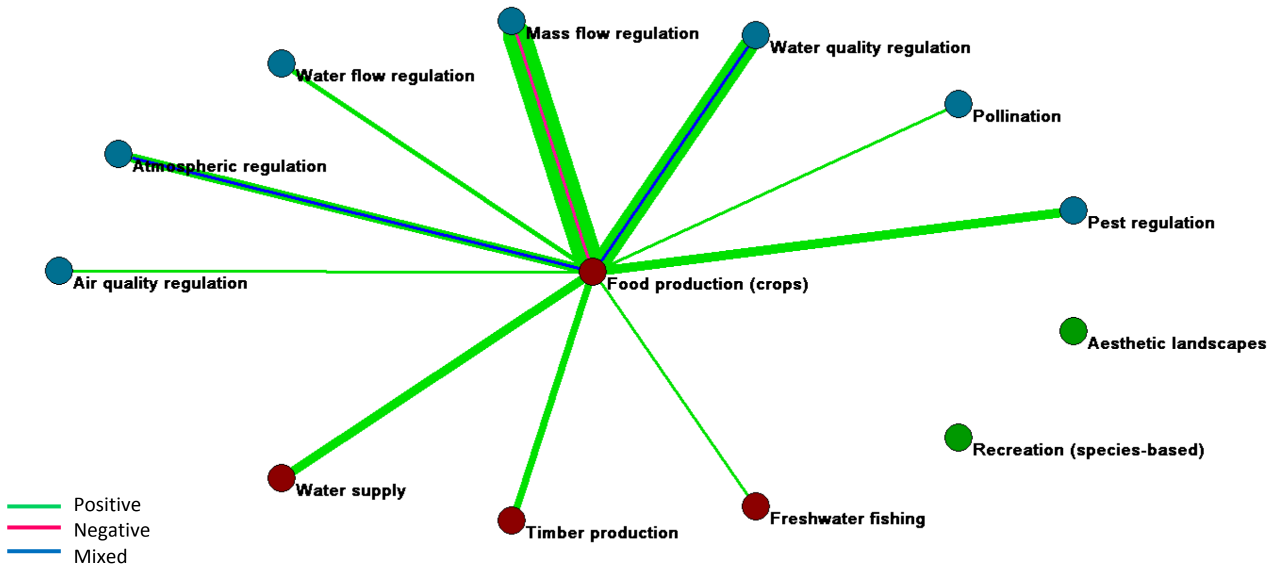

Figure 30: Interactions between food production and other ecosystem services (unclear interactions and those identified in reviews of the other services are omitted). Line thickness is proportional to number of studies citing the interaction.

One of the main interactions is with mass flow regulation. Soil erosion is a major problem in many parts of the world, and many of the studies explored farming methods that can help to reduce erosion, protect soil fertility and thus boost yields, using techniques such as cover crops, intercropping with trees or shrubs, and agroforestry. Many of these sustainable farming methods can increase soil carbon, and agroforestry can also provide a source of timber. However intensive farming can exacerbate soil erosion, so there were some negative interactions.

As water availability is a crucial factor for agriculture, it is not surprising that there are interactions with water flow regulation, water supply and water quality. Although intensive agriculture is often associated with water pollution from agrochemical use and over-abstraction of water, the interactions in the studies we reviewed were more often positive because the focus was only the use of sustainable techniques such as cover cropping that reduce fertiliser use. These sustainable farming techniques can also be beneficial in encouraging pollinators and pest predators.

There is considerable potential for management techniques to exploit the synergies and reduce the negative interactions associated with food production, and this is partly reflected in the number of European level policies mentioned in the review for this service, including the Biodiversity Strategy, Habitats Directive, Common Agriculture Policy, Nitrates Directive, Water Framework Directive and Environmental Impact Assessment. However, these policies are not applicable to non-European countries.

4.5 Air quality regulation

Urban trees are the primary vegetation capable of having an impact on air quality. They do this in two ways: firstly by physically intercepting airborne pollutants on the leaf surface or absorbing them through the leaf pores (stomata), and secondly (indirectly) by providing shade and shelter so that buildings require

less energy for heating and cooling, so that less pollution is generated. The literature included in this review focuses exclusively on the first method.

Around 80% of the studies reviewed are located in Europe or North America, and they are mainly local studies concerned with assessing the impacts of trees, green roofs or other urban vegetation on dry deposition of pollutants in one or more cities. The studies use a mix of primary data and modelling techniques, and the main indicators are air purification rates or deposition velocity (both typically measured in weight of pollutant removed per unit area per unit time), or changes in pollution concentrations (in weight of pollutant per cubic metre of air). Percentage tree cover is almost always an important parameter in the models.

The main provider of the service is urban vegetation, which can be classified as an entire community (urban vegetation), a specific functional group (urban trees) or a mix of specific species, depending on the context. Examples of all these ESPs were identified in the review, with a degree of overlap, and a range of species-, community- and functional group-level biotic attributes are identified as contributing to the service (Figure 31).

Two of the main attributes are leaf area index and canopy cover, both of which are classified under “Other biotic” as they were not in the original list of biotic attributes. Other key attributes are community/habitat area, typically referring to benefits of tree cover for pollution removal (e.g. Jim and Chen, 2008); functional diversity, which is found to enable pollution removal to be performed across varying conditions (Manes et al., 2012); and species size/weight with larger trees having a larger leaf area enabling them to trap airborne pollutants (Brack, 2002). All attributes except mortality have a predominantly beneficial impact, but there are some negative impacts. Several studies assess the impact of isoprene and other biogenic volatile organic compounds (BVOCs), which are emitted at far higher rates by certain tree species and can stimulate ozone production, though all these studies conclude that the net impact of urban trees on air quality is beneficial (e.g., Morani et al., 2011). Five studies present evidence that trees planted along busy roads can create a canyon effect that prevents atmospheric mixing of polluted air and lowers air quality (e.g. Salmond et al., 2013).

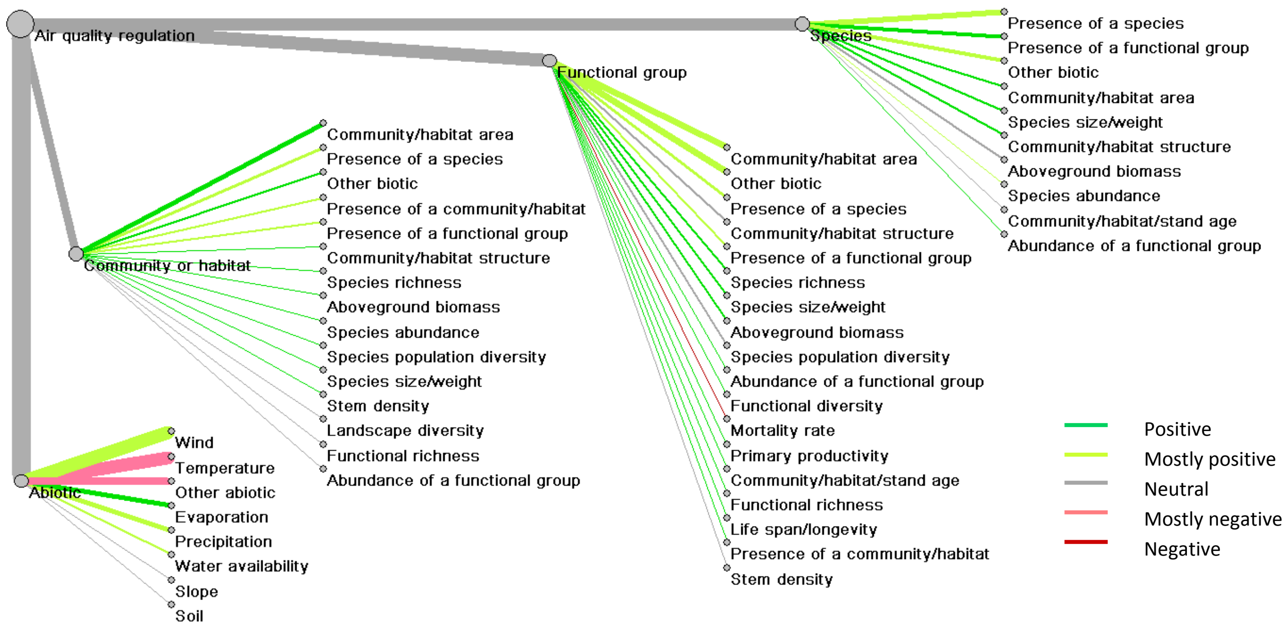

Figure 31: Network diagram showing linkages between ESPs, biotic attributes and abiotic factors for the service of air quality regulation. Line thickness indicates the number of studies showing a given link.

Abiotic factors, particularly those involved in the mechanics of atmospheric mixing or air flow, have highly complex and non-linear relationships with the contribution of urban trees to air quality regulation. Relationships described in the studies reviewed are highly context dependent. For example, factors related to air movement (i.e. wind direction, wind speed and boundary layer height) can either increase deposition rates on plant surfaces or increase re-suspension of particulates, depending on the factor's magnitude and on the spatial and temporal context (e.g. the interactions with topography and physical structure of the vegetation; Freiman et al., 2006; Nowak et al., 2006). Similarly, high temperatures can decrease the uptake of pollutants by plants (e.g. Alonso et al., 2011) and can also reduce air quality by increasing the rate of ground level ozone production from BVOCs (Salmond et al., 2011). However, temperature can have an almost purely positive effect on air quality regulation over ranges where it increases plant growth and metabolism. Simplified generalisations about the relationship between abiotic factors and air quality regulation are therefore largely impossible.

Urban environments are highly managed ecosystems, and therefore human management is integral to the air quality regulation provided by urban trees. Urban trees and shrubs are managed either directly through planting and maintenance (watering, pruning, feeding), or indirectly by protecting surrounding woodland areas from development. Where these management activities increase the extent of urban vegetation, air quality regulation generally increases. The only exceptions to this were cases where planting efforts either utilised species with higher BVOC emission rates or resulted in tree configurations that prevented adequate mixing of polluted air.

Thresholds are mentioned only in the context of air pollution standards above which there is presumed to be a negative health impact. Vegetation removal of airborne pollutants is generally regarded as an asymptotic function of vegetation cover, so it seems unlikely that a threshold value of vegetation cover that is necessary to sustain this service could be identified.

Overall, the evidence for substantial air quality benefits from urban vegetation was found to be weak, with many of the studies relying on modelling and plant chamber experiments, and little empirical evidence in a real urban setting. Moreover, both modelled and empirical data generally indicate that the proportion of airborne pollutants removed by urban vegetation is low (Setala et al., 2013). However, as shown in Figure 32, virtually all of the studies reviewed emphasise the positive contributions urban trees and other vegetation made to other ecosystem services. The most frequently cited interaction is with microclimate regulation (21 studies), which is classified as "other" (not shown), but studies also identified benefits for aesthetic landscapes (18 studies), atmospheric regulation (16 studies), mass flow regulation (6 studies), water flow regulation (14 studies), recreation (7 studies) and timber production (3 studies). The only negative interaction is with pest regulation, as trees can provide habitat for insect pests.

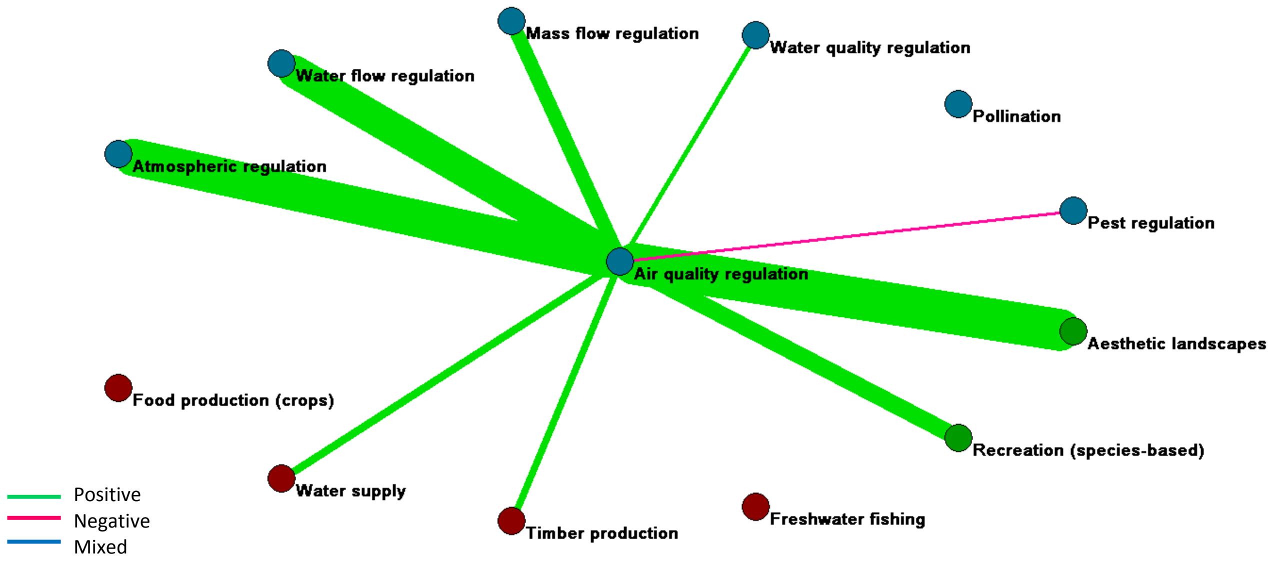

Figure 32: Interactions between air quality regulation and other ecosystem services (unclear interactions and those identified in reviews of the other services are omitted). Line thickness is proportional to number of studies citing the interaction.

4.6 Atmospheric regulation (carbon sequestration)

Most of the studies on atmospheric regulation are experimental measurements of vegetation biomass at a particular local site – often sampling a group of plots in a forest, or comparing two different habitats such as forest and farmland, or logged forest and intact forest. The estimates of biomass are then used to estimate carbon storage in tons per hectare, or carbon sequestration in tons/hectare/year. All continents are represented, though 81% of the studies are in North America, Europe or Asia.

Most of the studies assess the service at the level of the entire community or habitat, which can include not just trees and shrubs but also grass, understory plants, dead wood, leaf litter and soil carbon. However, some studies focus on specific species or functional groups (Figure 33Figure 39).

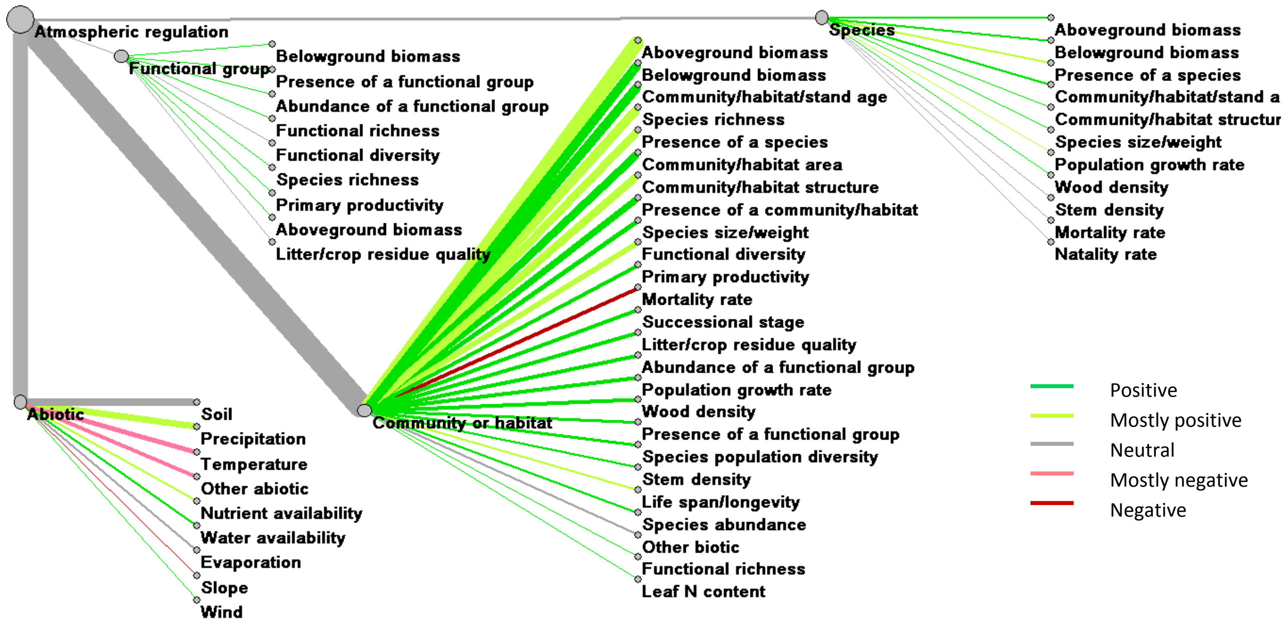

Figure 33: Network diagram showing linkages between ESPs, biotic attributes and abiotic factors for the service of atmospheric regulation (carbon storage). Line thickness indicates the number of studies showing a given link.

The literature shows that this service is affected by a large range of attributes, both biotic and abiotic, and the influence is mainly positive. The main determinant of carbon storage is simply the amount of biomass, so key attributes are community (forest) area, above- and below-ground biomass, stand age, primary productivity, growth rate and species size/weight. For example, Kirby and Potvin (2007) find that trees with diameter at breast height (DBH) over 10cm account for 90% of the aboveground carbon stocks in the forest area studied. A number of studies investigate the impact of species richness, functional richness, functional diversity and structural diversity, finding that this has a positive impact in many studies, but that sometimes a less diverse mix could store more carbon if it consists of large tree species. Chen (2006) reports that carbon storage increases with species richness but that it may saturate at a low number of species, after which it increases more slowly: this is the only example of a threshold found in the review. Many of the more recent articles highlight an interesting debate over the role of niche complementarity versus the selection effect, which is discussed in detail in the report on atmospheric regulation in Annex 5. Mortality rate is the only attribute to negatively affect carbon storage, for example as a result of wildfire (e.g. Haugaasen et al., 2003), pests such as bark beetle (Seidl et al., 2008), or grazing (Klumpp et al., 2009).

The relationships between abiotic factors and atmospheric regulation are less clear, with the review finding that these are highly dependent on the ecosystem and location considered. Factors include water availability, precipitation, evaporation, temperature and soil (including the effect of pH; Keeton et al., 2010; and soil moisture; Yurova and Lankreiger, 2007). Drought and high temperatures, both exacerbated by climate change, are often cited as having a negative impact on this service (e.g. Beier et al., 2009, Law et al., 2003), and wildfire occurrence is an additional (often related) abiotic factor (e.g. Wardle et al., 2012).

Human impacts are mainly negative, through logging and over-harvesting of forest products, grazing, forest fires and urban development. However, there are also examples of positive impacts where there is management to promote biodiversity and ecosystem services, such as on organic coffee farms (Hager,

2012) or no-till farming to enhance soil carbon (Mishra et al., 2010), or where forest or grassland that has been damaged by logging or overgrazing is now being protected or restored. Fourteen articles mention policies to promote carbon storage, including REDD and the Clean Development Mechanism as well as some national and local policies such as logging bans or forestry management.

Figure 34 shows a wide range of mainly positive interactions between atmospheric regulation and other ecosystem services, reflecting the multiple benefits of forests for services such as water flow and mass flow regulation, air quality, recreation and aesthetic landscapes. The interactions with timber production are complex, and can be positive or negative depending on whether the timber is produced sustainably. There are also negative interactions with food production due to deforestation to clear land for farming, although there are also benefits for crop yield from farming techniques that improve soil carbon storage. One article mentioned possible negative water quality impacts of a forestry plantation.

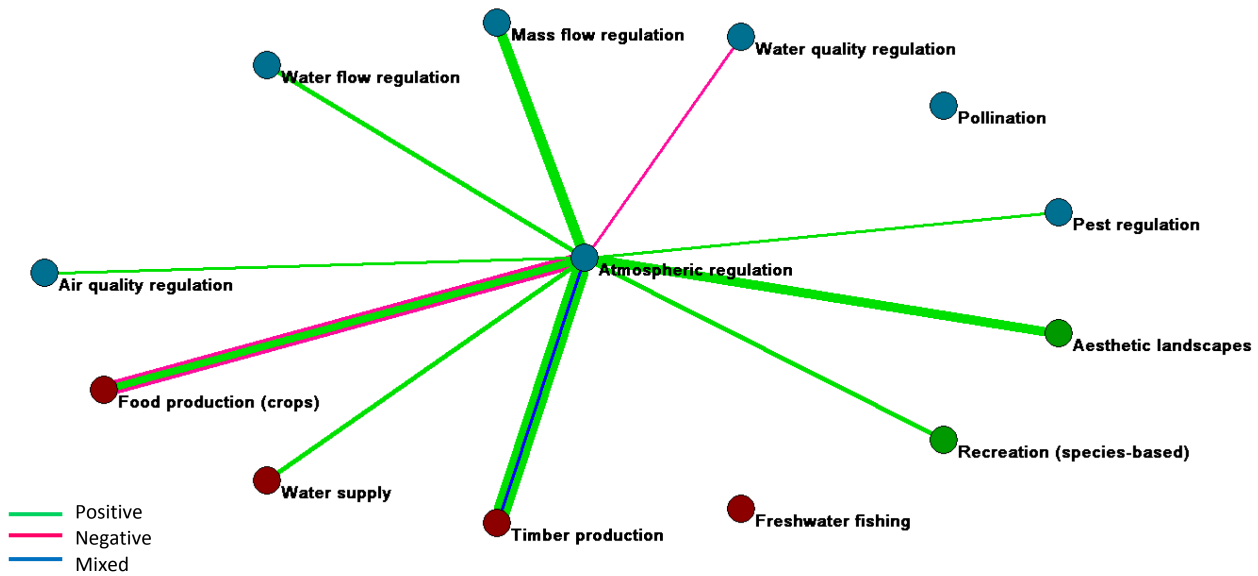

Figure 34: Interactions between atmospheric regulation and other ecosystem services (unclear interactions and those identified in reviews of the other services are omitted). Line thickness is proportional to number of studies citing the interaction.

4.7 Mass flow regulation (erosion protection)

For mass flow regulation, almost half of the studies reviewed are from Europe, often from mountainous or Mediterranean areas where soil erosion is a common problem. Studies typically measure soil erosion empirically, in units such as kg/m^2/year. Most of the studies focus on the role of vegetation cover in stabilising soil. They generally refer to the impact of the entire community/habitat, but some examine or compare specific species or functional groups. The overall impact of biotic attributes is positive, with no predominantly negative or unclear relationships (Figure 35).

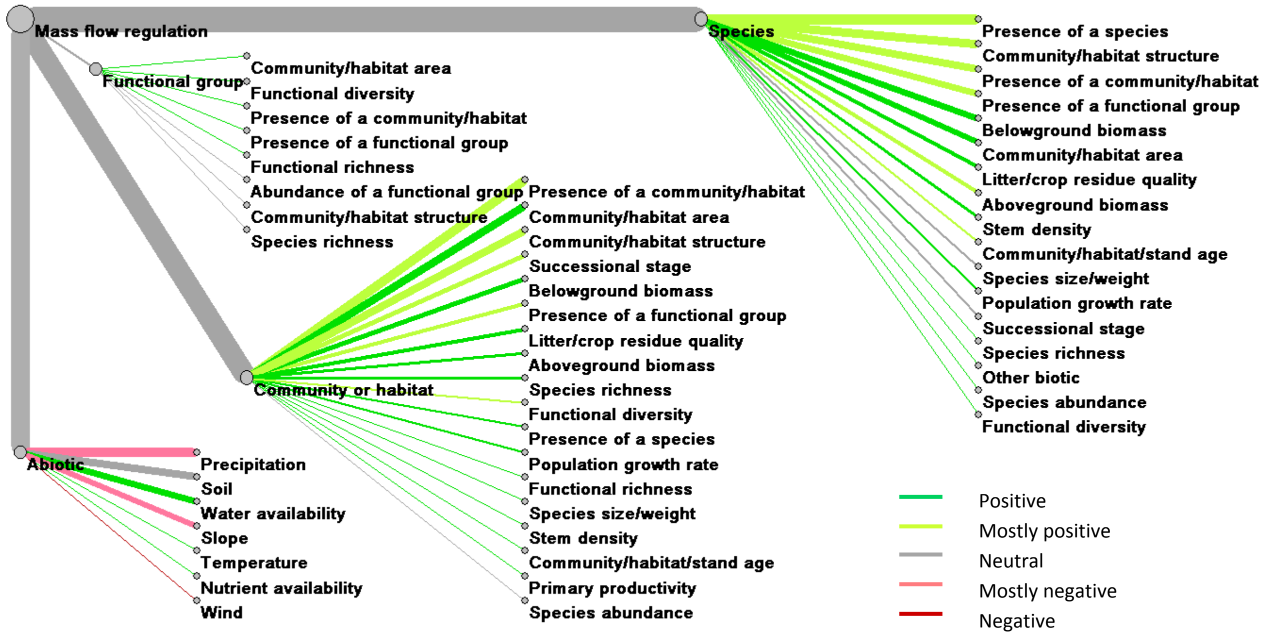

Figure 35: Network diagram showing linkages between ESPs, biotic attributes and abiotic factors for the service of mass flow regulation (erosion protection). Line thickness indicates the number of studies showing a given link.

The review found that the presence of some form of vegetation, generally a specific habitat (e.g. grassland), but sometimes a functional group (trees or shrubs) or specific species (e.g. Stipa grasses), is the most important factor in providing this service. For example, grassland is found to reduce soil erosion when compared to cropland and forest has lower erosion rates than both cropland and grassland (Wei et al., 2010). Older and taller vegetation tends to have a more stabilising effect, so community structure, age, above- and below-ground biomass and successional stage all have positive impacts.

For the abiotic factors, precipitation and steeper slopes are the main factors that increase erosion, with soil characteristics also being frequently discussed. However, in drier climates low rainfall can be associated with greater erosion because it reduces vegetation cover, such as in a study of Mediterranean shrubland by Kosmas et al. (1997).

Human management was mentioned in 75% of the articles, with most mentioning negative impacts from activities such as crop cultivation, overgrazing and deforestation alongside positive impacts from efforts to restore vegetation cover. Despite the widespread nature of the problem, there was little mention of policies to address soil erosion, with just one mention of the Common Agricultural Policy and one of the

Soil Thematic Strategy, plus a few local or national policies including the Grain for Green programme in China.

Mass flow regulation has synergies with many other ecosystem services (Figure 36). Planting vegetation on steep slopes to reduce soil erosion, or increasing the organic content of the soil to improve infiltration, will also help with flood protection, water quality regulation (reducing pollution from agricultural runoff) and carbon storage, as well as improving the aesthetic value of the landscape. There are mixed interactions with food production: reducing loss of soil from fields is beneficial for farming, but mechanical cultivation or over-grazing can cause erosion.

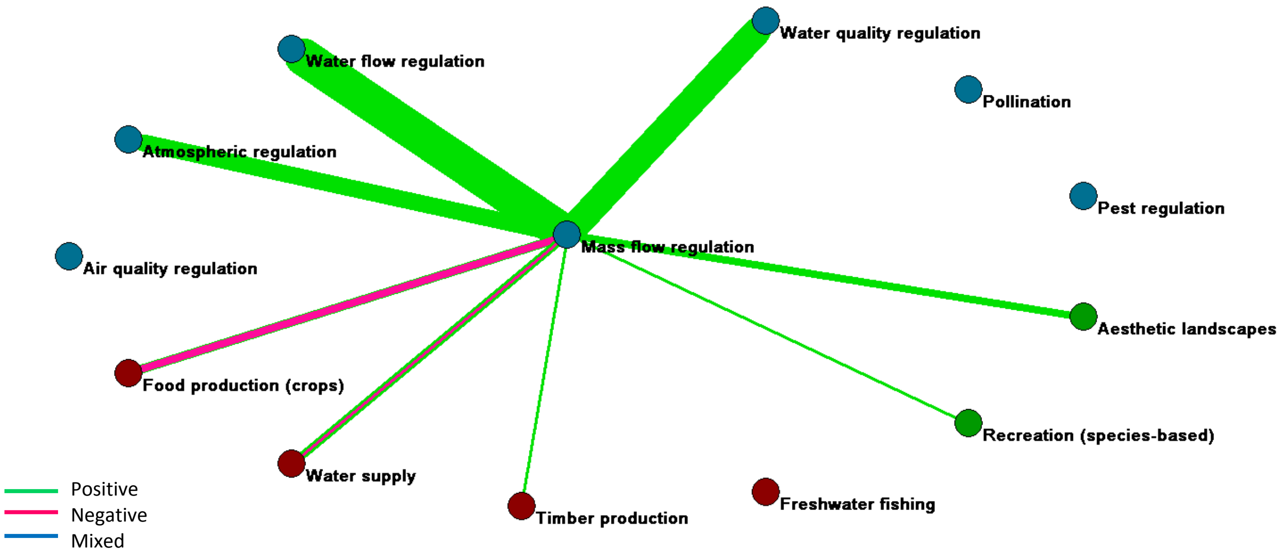

Figure 36: Interactions between mass flow regulation and other ecosystem services (unclear interactions and those identified in reviews of the other services are omitted). Line thickness is proportional to number of studies citing the interaction.

4.8 Water flow regulation (flood protection)

Ecosystems can provide a flood protection service in several ways:

(i) Forests and other vegetation intercept precipitation, increasing the rate at which it evaporates before reaching the ground;
(ii) Plants suck up water from the ground and release it into the air through transpiration;
(iii) Plant roots can increase the rate at which water infiltrates into the ground, and plant litter can increase the organic content of the soil which also improves infiltration;
(iv) Wetland areas, when not completely saturated, can act as a sink for surface runoff;
(v) Coastal vegetation can reduce the speed and height of waves, providing protection against floods during storms and tsunamis.

Flood protection is not always directly assessed in the literature, but it is possible to use proxy indicators, usually reductions in peak stream flow or (for coastal areas) reductions in wave height. The literature includes examples of all the above mechanisms, but most of the studies reviewed investigate the role of forests in reducing surface runoff, typically through "paired catchment" studies that compare empirical

measurements of stream flow in similar-sized forested and unforested catchments. For this reason, it was generally inferred that water flow regulation was provided by the entire community or habitat, usually forests, though some studies examine the role of individual species (Figure 37).

The studies are located mainly in Europe (29 studies, of which 13 are in the UK), North America (13 studies) and Asia (9 studies, of which 4 are in China). Almost half of the studies use long-term data sets, to capture stream flow under a range of rainfall conditions.

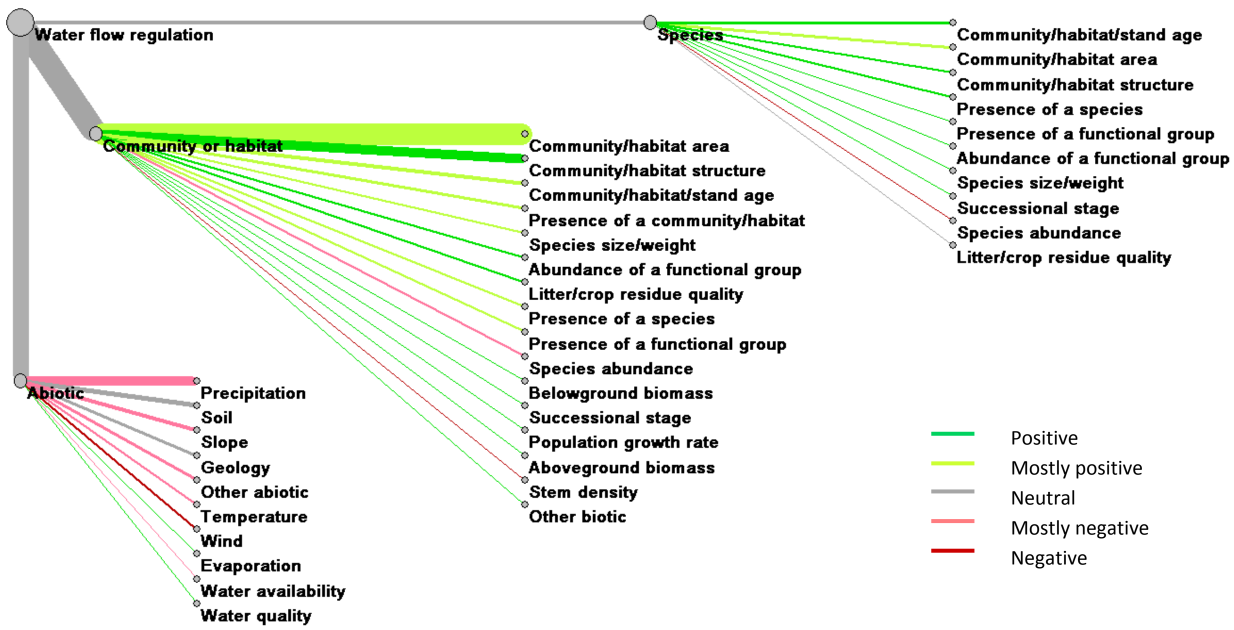

Figure 37: Network diagram showing linkages between ESPs, biotic attributes and abiotic factors for the service of water flow regulation (flood protection). Line thickness indicates the number of studies showing a given link.

Community/habitat area is the most commonly identified biotic attribute, with most articles observing that forests tend to reduce peak run-off (by intercepting precipitation, absorbing groundwater through transpiration and improving the infiltration capacity of the soil). As larger trees tend to intercept and absorb more water, stand age and community structure are also cited a number of times, as are above- and below-ground biomass, successional stage, species size/weight and growth rate. Several studies show a positive impact of litter quality on rainwater infiltration rates. Although most studies examine forests, some investigate the role of wetlands, which can provide a sink for floodwater provided that they are not already saturated, and coastal vegetation such as mangroves, which can provide an important physical barrier against high waves generated during storms or tsunamis. In three studies, however, species abundance is cited as having a negative impact on flood protection as a result of invasive species reducing river channel capacity and trapping sediment. These include mangrove (*Kandelia candel*) (Lee and Shih, 2004), willow (Erskine and Webb, 2003) and tamarisk (Zavaleta, 2000). Interestingly, this is the only service for which no attributes connected to species or functional richness or diversity were mentioned in the literature, although structural complexity was found to be beneficial.

Abiotic factors are often cited in the literature. The impact of precipitation is debated, with some articles challenging the established view that forests provide diminishing levels of protection for higher rainfall

events (e.g. Green and Alila, 2012). Several articles illustrate ways in which climate change can reduce the ability of ecosystems to provide flood protection: these include the damaging impact of rising sea levels on coastal wetlands (Wamsley et al., 2010); the degradation of coral reefs due to rising temperatures (Ferrario et al., 2014); and damage to coastal marsh vegetation due to more frequent storms (Möller et al., 2007). Steeper slopes are associated with a more rapid downward movement of water (Nedkov and Burkhard, 2012) and a larger volume of runoff (Lana-Renault et al., 2014).

Human impacts are predominantly negative (17 studies), due to deforestation, soil compaction, or over-grazing of marshes and grassland. Even after abandonment of farmland, long-term negative impacts on soil structure can persist. However, six studies cite positive impacts from restoration of forests, mangroves, wetlands, coral reefs or riparian ecosystems. Three examples of thresholds were found, including an estimate that the flood protection service would start to decline after 20-30% of a catchment area was deforested (Schnorbus and Alila, 2013).

Multiple interactions with other ecosystem services were found (Figure 38). There are many positive synergies, relating to the benefits of forests, wetlands and coastal mangroves for water and air quality regulation, atmospheric regulation, landscape aesthetics, mass flow regulation, recreation and pollination. In urban areas, green roofs can also contribute to air quality regulation and cooling. However, there can also be trade-offs: raising the water level in wetlands would have a beneficial effect on wildlife and biodiversity but would reduce the flood storage capacity, for example. There is often a negative correlation with the service of freshwater supply, because the absorption of water by forests tends to reduce stream low-flows as well as peak flows, which can exacerbate water shortages in regions where water supply is limited. Several of the studies provided empirical evidence for this, as the catchment studies often measured both peak flows and low flows. However, some authors found that forests can both reduce peak flows and enhance low flows, through improving soil porosity and infiltration of surface runoff, thus providing a long-term store of groundwater to be released over time.

There are negative interactions with the services of timber and food production, due to forest clearance for timber or agriculture, though some studies cite the establishment of timber plantations on former grassland as a positive benefit in terms of reduction of flood risk.

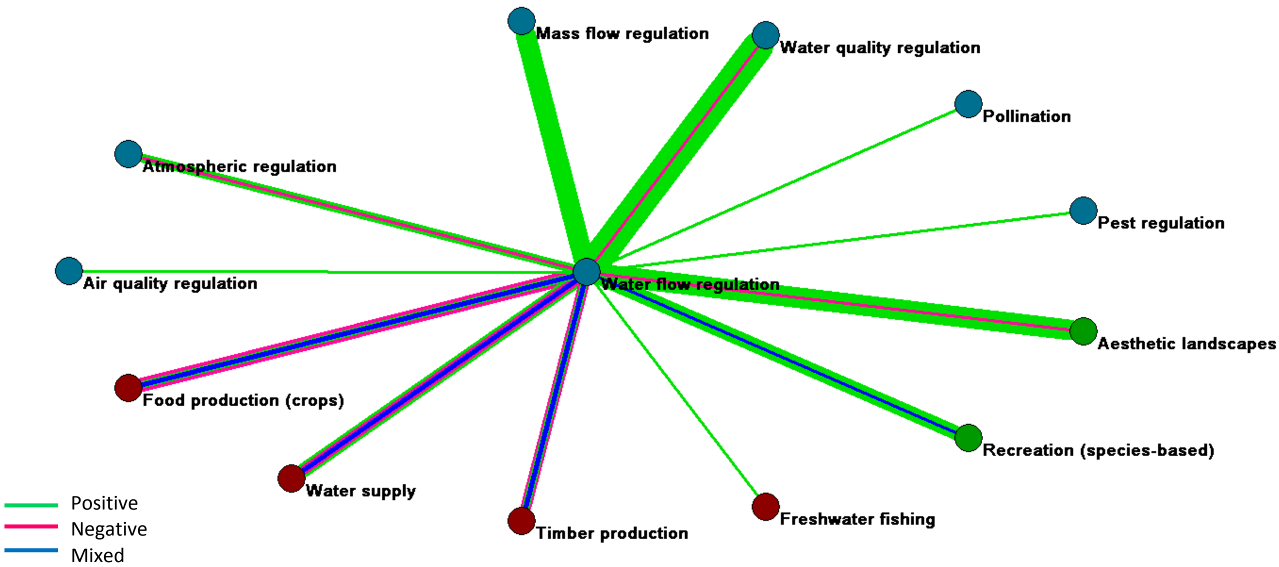

Figure 38: Interactions between water flow regulation (flood protection) and other ecosystem services (unclear interactions and those identified in reviews of the other services are omitted). Line thickness is proportional to number of studies citing the interaction.

Perhaps reflecting the many interactions with other services, a variety of different policies were mentioned in the literature, including the Common Agriculture Policy, the Water Framework Directive and the Habitat Directive (each mentioned four times).

4.9 Water quality regulation

Most of the 60 studies reviewed for the service of water quality regulation examine the impact of entire communities or habitats, with forests and wetlands being most commonly cited, though 13 studies focus on specific species populations (e.g. common reed) and one assessed the role of two functional groups (submerged macrophytes and zooplankton) (Figure 39).

The articles reviewed include large-scale land use studies such as the impact of deforestation on water quality in rivers and lakes; smaller scale experimental studies of the impact of vegetation type on water quality in wetlands; and studies of the impact of riparian buffer zones along streams and rivers. Almost half of the studies (28/60) were located in North America, with 13 in Asia and only eight in Europe. The main indicators were direct measurements of water quality, typically concentrations of various forms of nitrogen and phosphorous and/or suspended sediments, and measurements of nutrient removal rates.

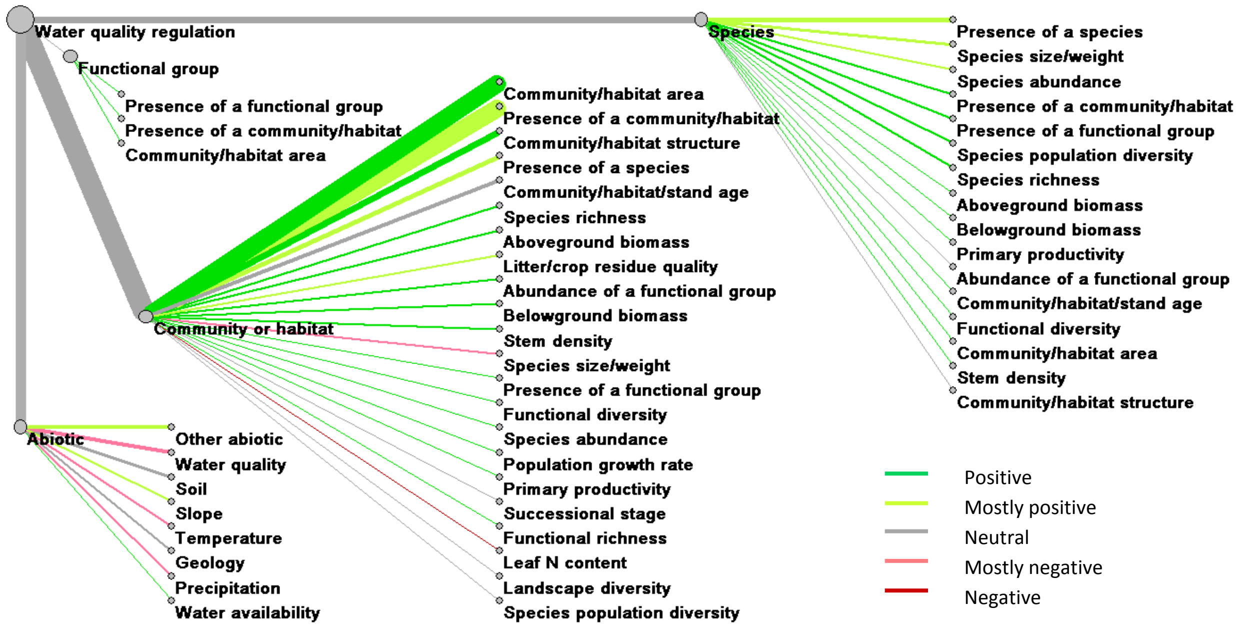

Figure 39: Network diagram showing linkages between ESPs, biotic attributes and abiotic factors for the service of water quality regulation. Line thickness indicates the number of studies showing a given link.

The review identifies a number of ways in which ecosystems such as forests, wetlands and grassland can improve water quality:

(i) Permanent vegetation reduces soil erosion compared to bare ground or farmland;
(ii) Vegetation and marshes can trap sediment before it reaches water courses;
(iii) Vegetation can absorb and adsorb excess nutrients and other impurities;
(iv) Soils can host de-nitrifying bacteria that break down nitrates from fertiliser runoff into harmless nitrogen gas;
(v) Vegetation roots can improve infiltration, allowing more impurities to be filtered out by the soil and preventing pollution of adjacent streams and lakes.

Because of the role of vegetation in preventing erosion, physically trapping sediment and absorbing pollution, biotic attributes related to the amount of vegetation are found to have a positive impact. By far the most commonly cited attributes are the presence of a specific community/habitat (43 studies) and community/habitat area (40 studies), but community / habitat structure and age, above- and below-ground biomass, primary productivity, stand age, stem density and species size or weight are all found to have a generally positive impact. There are a few exceptions, with some studies finding that younger forest with a high density of small trees was more effective at filtering out pollutants than more mature forest with widely spaced trees (de Souza et al., 2013). Several studies focus on the abundance of highly effective species, such as California bulrush, poplar, willow or seagrass, or functional groups such as mangroves.

Ten studies also find an impact from various types of diversity, including species richness, species population diversity, functional richness and functional diversity. The impacts are predominantly positive and seem to be related to the ability of more diverse mixtures to be more productive, and therefore take up more nutrients, due to niche complementarity (i.e. exploitation of a wider range of resources) (Fisher et al., 2009; Cardinale, 2011). However, in two studies the impact is unclear, with Cardinale et al. (2011) stating that there is no evidence that polycultures out-perform the most efficient monocultures. Similarly,

Weisner and Thiere (2010) found that wetlands dominated by a less diverse mix of tall, emergent vegetation are more efficient at nitrogen removal. These two studies therefore demonstrate the selection effect rather than the niche complementarity effect.

The main abiotic factor cited in the literature is, unsurprisingly, water quality. This is classified as having a mainly negative impact as badly polluted water can damage the ecosystem, reducing its ability to provide the service. Other abiotic factors mentioned include temperature, slope, precipitation, and soil. The relationship with water quality regulation is often unclear or mixed (both positive and negative), and varies between studies. For example, Tomimatsu et al. (2014) find that higher temperatures in summer speed up nitrogen removal in wetlands due to higher plant growth rates, but Rodrigo et al. (2013) find that warmer weather stimulates algal blooms.

A range of human impacts were noted, including negative impacts from deforestation, degradation of wetlands, urbanisation and pollution from agricultural fertilisers, pesticides and sewage. However, some articles cite benefits from restoration of wetlands, construction of artificial wetlands, afforestation, protection of forests and wetlands, and planting of riparian buffer strips.

Twelve articles refer to some kind of threshold, including minimum safe standards for water quality, or percentage land use in catchment areas. Negative impacts on water quality are seen beyond certain thresholds, including 40-60% removal of indigenous vegetation, 10% impervious surfaces, 50% of land use in a catchment for agriculture, and 20% urbanisation. One study finds that minimum levels of richness, evenness and diversity are required for a microbial community to perform denitrification. However, Cardinale et al. (2011) found a saturation effect whereby ecosystem function ceased to improve after a certain level of species richness.

Links to other ecosystem services are mentioned in 19 studies, comprising a complex mix of positive and negative interactions (Figure 40). For example, fertilisers from timber and crop production are a cause of water pollution, but cleaner water supplies are also beneficial for irrigation of food crops such as rice, and riparian buffer strips can be a source of sustainably harvested timber. Similarly, carbon is sequestered in forests and in wetland soils, but wetlands can also be a source of methane and nitrous oxide, two powerful greenhouse gases. However, forests and wetlands also have mainly positive benefits for fishing, mass flow regulation, water flow regulation, aesthetic landscapes and pest regulation.

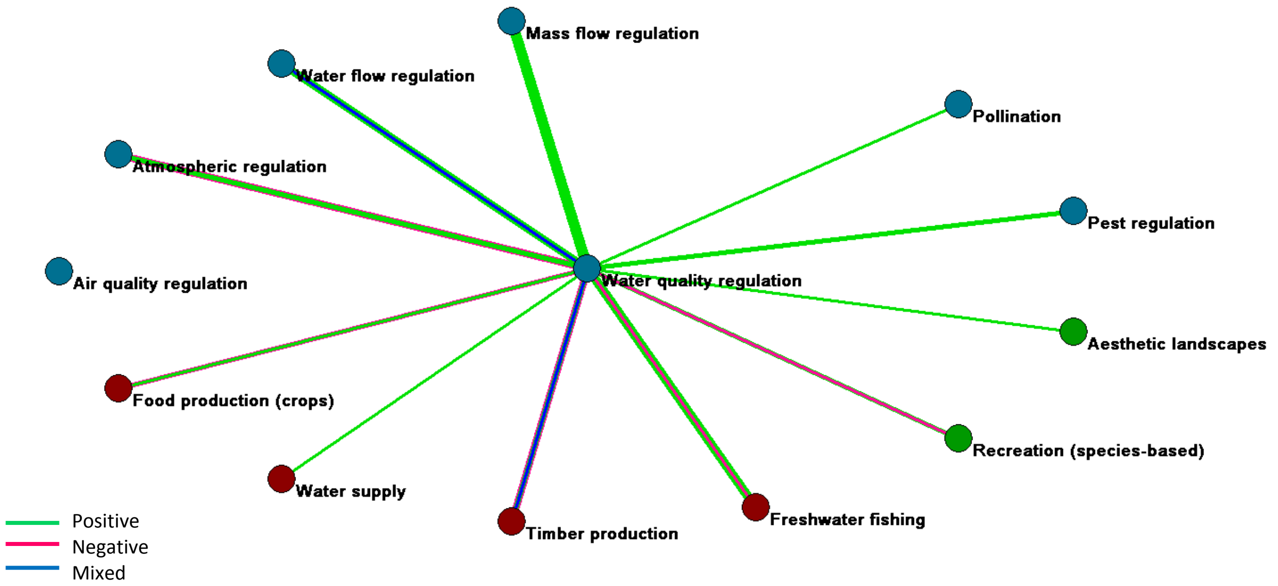

Figure 40: Interactions between water quality regulation and other ecosystem services (unclear interactions and those identified in reviews of the other services are omitted). Line thickness is proportional to number of studies citing the interaction.

4.10 Pollination

The studies spanned a wide range of locations from all over the world, but most were conducted in Europe (24) or North America (16). Most of the articles on pollination refer either to the functional group of pollinating insects, or to specific species populations (e.g. honey bees, bumble bees, hoverflies) (Figure 41). It is difficult to measure pollination effectiveness directly, so a range of proxy indicators were used, including crop yield, fruit or seed set, the number of pollinating insects, the percentage of natural land cover, or distance of agricultural fields to natural or semi-natural habitats.

The most commonly cited biotic attribute is the presence of a functional group (33 counts). Related to this, the abundance of a functional group (23 counts), presence of particular species (22 counts) and abundance of species (27 counts) are also important, with behavioural traits such as foraging distance, flight range, pollinator size, and bee tongue length (Bommarco et al., 2011) being important in determining which pollinators can access certain flowers (23 counts). However, the second most common attribute is community/habitat structure (30 counts), emphasising the importance of nearby habitats in providing shelter for pollinators and alternative food when crops are harvested. Many articles mentioned that a diverse, natural habitat with a variety of flowering plants was needed to support populations of pollinators. Pollinating services and the diversity of pollinators tended to decline with increasing distance from natural habitat (e.g. Carvalheiro et al., 2010).

Diversity appears to be very important for pollination, with species richness being the third most frequently cited attribute (28 counts). Studies refer both to the diversity of the pollinators, and to the diversity of the plant species in the habitats needed to sustain the pollinators. The impact of pollinator diversity is mainly positive, with various studies finding that more diverse populations of pollinators increased seed production (e.g. Albrecht et al., 2007), coffee fruit set (e.g. Vergara and Badano, 2009) and pollination

efficiency (Hoehn et al., 2008; Balvanera et al., 2005). This is generally because different species visit different plants (Winfree et al., 2008) or visit different areas and at different times (Hoehn et al., 2008), so that a more diverse community provides a more complete pollination service. Many articles also discuss the need for plant species richness and functional diversity in the surrounding habitat, in order to support populations of pollinators (e.g. Holzschuh et al., 2011). In fact, the strong relationship between plant diversity and pollinator diversity is demonstrated by Batary et al. (2010) who find that the richness of insect-pollinated plant species is directly correlated with bee species richness in three different European countries. The relationship works both ways, with Fontaine et al. (2006) showing that after two years, plant communities pollinated by more functionally diverse pollinator assemblages contained about 50% more species than those pollinated by less diverse assemblages. However, there are also examples of negative impacts on pollination, associated with the introduction of honey bees which compete with native bees (Shavit et al., 2009; Badano and Vergara, 2011).

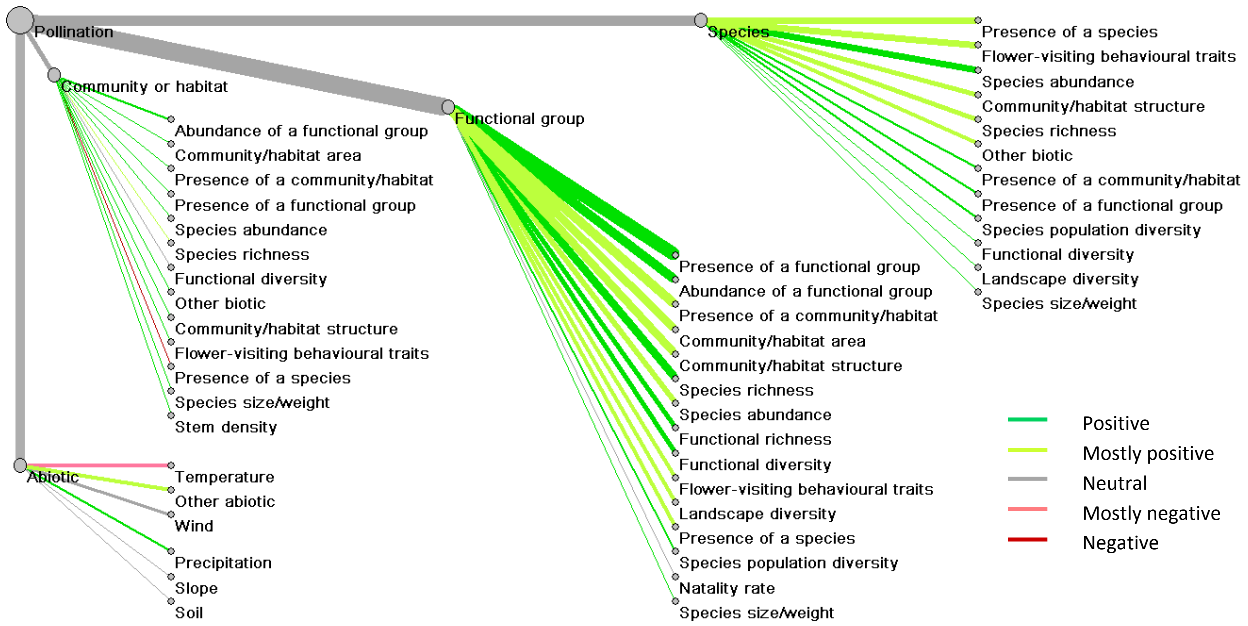

Figure 41: Network diagram showing linkages between ESPs, biotic attributes and abiotic factors for the service of pollination. Line thickness indicates the number of studies showing a given link.

Abiotic factors such as temperature and wind speed are mentioned in a number of journal articles, but the direction of impact on pollination is usually unclear.

Human input was found to have a negative impact on pollination in 18 studies, due to loss or degradation of natural habitat and the use of pesticides and fertilisers. However, positive impacts were found in 3 studies and mixed impacts in 7 studies, from the effect of managed beehives in agricultural areas, or the conservation and protection of natural or semi-natural habitats in National Parks or urban gardens. Less intensive farming (e.g. extensive, organic farming) supports pollinator abundance and diversity and thus benefits pollination services. Several policies were mentioned in connection with this, including agri-environment schemes and organic farming policy. Only one threshold was found: a point in ecosystems where additional bee visits no longer increase production/productivity.

The review found 23 positive interactions with food production, for obvious reasons, but surprisingly there were few clear links to other ecosystem services including pest regulation (Figure 42). However, links between these two services were identified by the pest regulation review (see below).

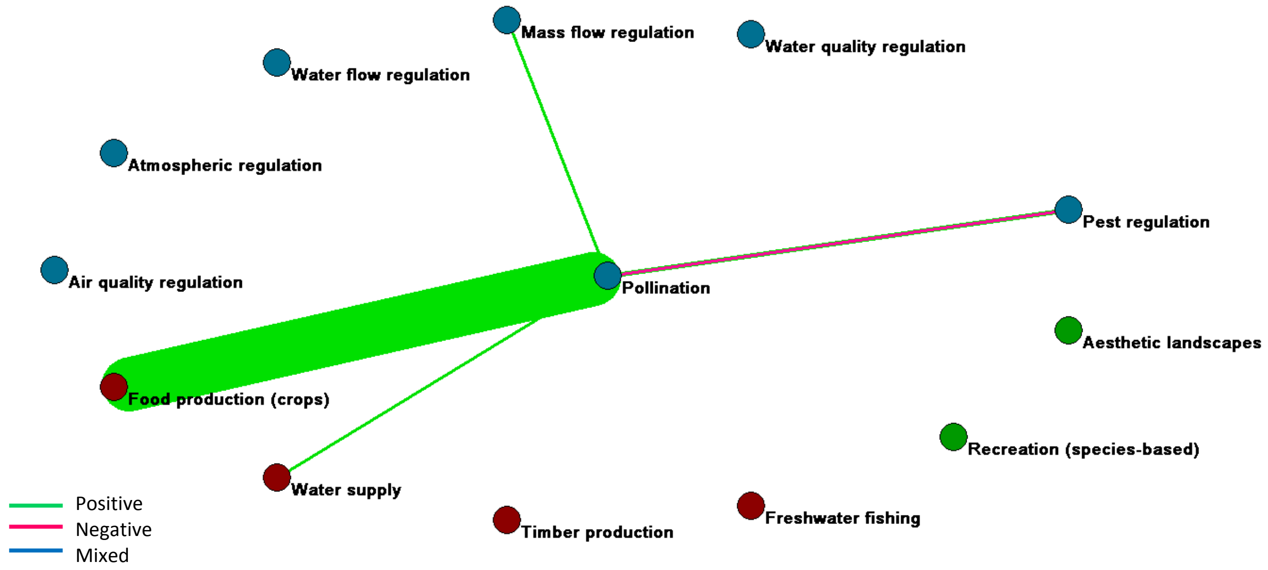

Figure 42: Interactions between pollination and other ecosystem services (unclear interactions and those identified in reviews of the other services are omitted). Line thickness is proportional to number of studies citing the interaction.

4.11 Pest Regulation

Pest regulation is mainly provided by functional groups, e.g. spiders, wasps or beetles, although 17 studies investigate specific species populations (both single and multiple) and six studies focus on an entire habitat/community (typically farmland) (Figure 43). The most commonly cited indicator is pest density, though many studies use the population or richness of pest predators as a proxy. Some articles also cite crop yield, pest damage or the cost of pest control.

This service is affected by a wide range of biotic attributes, with the linkages found to be predominantly positive. The most commonly cited attributes are community/habitat presence, area and structure, because many articles focus on the importance of natural or semi-natural habitats for supporting populations of pest predators. The studies find that pest predation is positively influenced by complex habitats (e.g. Bianchi et al., 2006); by crop lands interspersed with and/or surrounded by semi-natural habitat (e.g. Letourneau et al., 2012); by good connectivity between patches (e.g. Boccaccio and Petacchi, 2009); and by diverse plant communities (e.g. Drapela et al., 2008). Habitat management can therefore influence predator density through modifications such as thicker ground cover (Colloff et al., 2013) or creation of semi-natural field edges (Krauss et al., 2011).

Other important attributes include the presence and abundance of a specific functional group (i.e. predators), and species abundance. A number of studies found that species richness, functional richness and functional diversity are important, though while several find that land use management can enhance predator diversity, fewer demonstrate that predator diversity reduces pest activity. Those that do attribute this to niche complementarity, with different predators attacking different prey sizes, life stages,

population densities and behaviour (e.g. flying vs. ground dwelling), but other studies find no effect of diversity. Predator behavioural traits are also cited, such as the ability to disperse over long distances (e.g. Öberg, 2007) or the ability to form aggregations during dormancy so that they can hatch en masse and attack prey (Iperti, 1999). These linkages are predominantly positive.

A small range of abiotic factors are discussed in the literature, with temperature and precipitation being the most common, although the effect is variable.

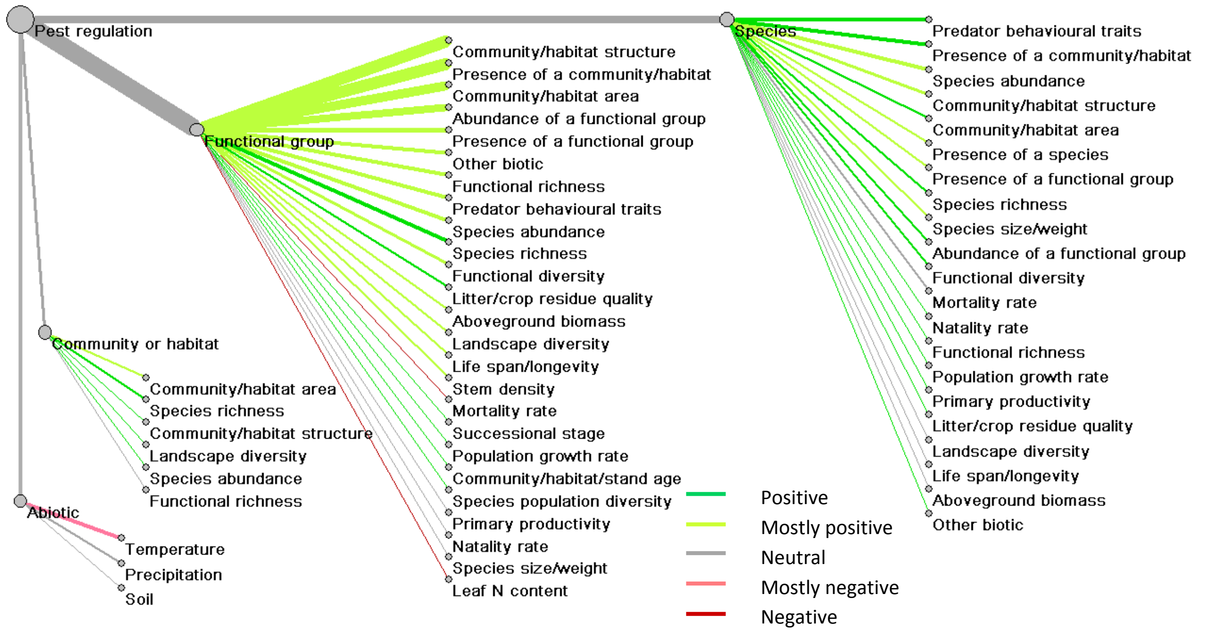

Figure 43: Network diagram showing linkages between ESPs, biotic attributes and abiotic factors for the service of pest regulation. Line thickness indicates the number of studies showing a given link.

The review found a mix of positive and negative impacts from human input and management, with examples of negative impacts mainly concerning habitat loss, and positive impacts including habitat improvement such as planting wildflower patches, mulching, thick groundcover between orchard rows, and less intensive rotations. One study identified a threshold related to the percentage of land covered by annual crops, finding that pest parasitism rates dropped precipitously when annual crop cover exceeded species-specific thresholds of 38% and 51% (Letourneau et al., 2012). However, only one study discusses the role of policy: Woodcock *et al*. (2014) discuss the potential for agri-environment schemes to increase the robustness of ecosystem services provided by pest control and pollination by conserving and creating semi-natural habitats.

Interactions with several other ecosystem services were identified (Figure 44). The main interaction, as expected, is with food production. Impacts were mainly positive, but there were some negative impacts as vegetation that provides refuges for pest predators can also shade the crops or compete for water and nutrients, thus reducing yield (e.g. Daghela Bisseleua et al., 2013), or provide refuge for pests (Bianchi et al., 2006). There were synergies with pollination, as semi-natural habitat can benefit both pollinators and pest predators, but also some trade-offs as pest predators can sometimes prey on pollinators or compete with them for food. Synergies were also mentioned with recreation (the value of bats for eco-tourism), water flow regulation and timber production (from agroforestry).

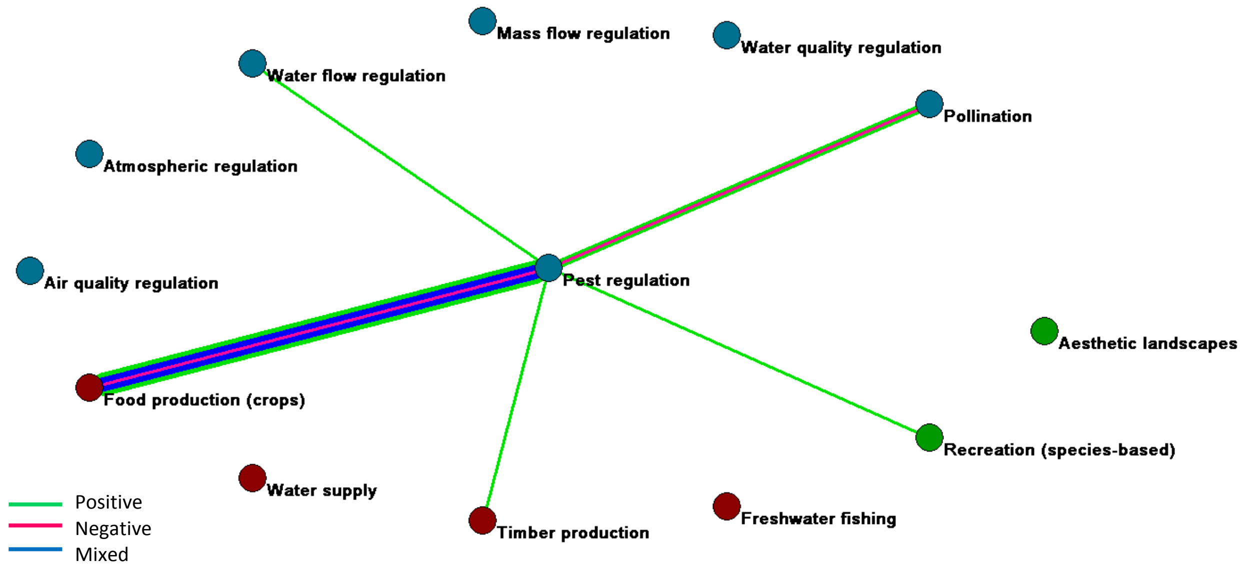

Figure 44: Interactions between pest regulation and other ecosystem services (unclear interactions and those identified in reviews of the other services are omitted). Line thickness is proportional to number of studies citing the interaction.

4.12 Recreation (species-based)

Species-based recreation is generally based in national parks or nature reserves, and includes activities such as wildlife viewing, hunting or fishing. Wildlife viewing is often assessed based on tourist surveys, while hunting and fishing may be assessed using evidence such as catch per unit effort or exploitation rates. A very wide variety of indicators were used, some related to humans, such as visitor numbers, distance to protected area, cost per trip, viewing preferences or willingness to pay for an experience, and some related to the ecosystem itself, such as area of protected land, bird species richness or fish abundance.

Not surprisingly, species-based recreation is found to be predominantly provided by specific species populations, though in 19 studies the focus is an entire community/habitat (e.g. coral reefs, nature reserves or hunting areas) (Figure 45).

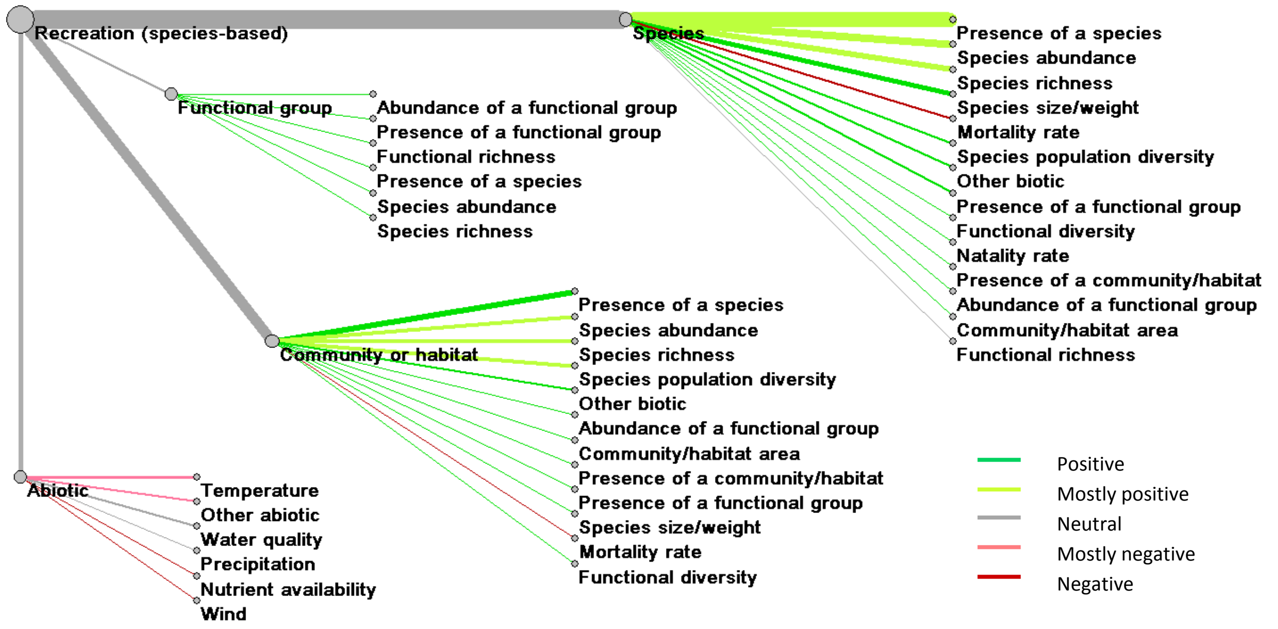

Figure 45: Network diagram showing linkages between ESPs, biotic attributes and abiotic factors for the service of species-based recreation. Line thickness indicates the number of studies showing a given link.

Biotic attributes are found to affect this service in a predominantly positive way, with the only negative impacts arising from mortality rate. The most important biotic attributes are the presence and abundance of specific species. These include charismatic species such as whales and dolphins for marine eco-tourism, or large mammals such as lions, tigers and elephants for land-based eco-tourism, as well as mammals such as deer for hunting, and fish such as salmon and trout for recreational fishing. Species size or weight can also be significant, with visitors, fishermen and hunters often expressing a preference for larger species such as sharks and lions. Species richness and diversity are also valued. For example, Lindsey et al. (2007) find that tourists in South Africa consider functional group diversity (in this case, the variety of large mammals) to be the most important feature of their wildlife viewing experience, and Ruiz-Frau et al. (2013) find that marine biodiversity is important for scuba divers.

A number of abiotic factors are cited in the literature. Weather-related factors such as precipitation and temperature are often cited, especially for fishing (e.g. Smallwood et al., 2006). These have mixed effects, with extreme conditions found to negatively affect recreation (Cooke and Suski, 2005).

As most of the studies were located in actively managed or protected areas such as national parks, all of the studies were classified as having some kind of human management. This typically had both positive and negative effects: the main impact was generally positive, due to protection of the wildlife in the area, but there could also be negative impacts from visitors such as disturbance to wildlife. As a result, many of the studies discussed methods of minimising these impacts, such as regulating fish catch, restricting hunting or limiting visitor numbers. Good governance, including the active participation of local communities, was shown to be important to maximise conservation benefits, enforce regulations and minimise problems such as poaching. There were several mentions of local or national regulations applicable to hunting, fishing and national park management, but the EU Habitats Directive was only mentioned twice.

A few interactions with other ecosystem services were identified (

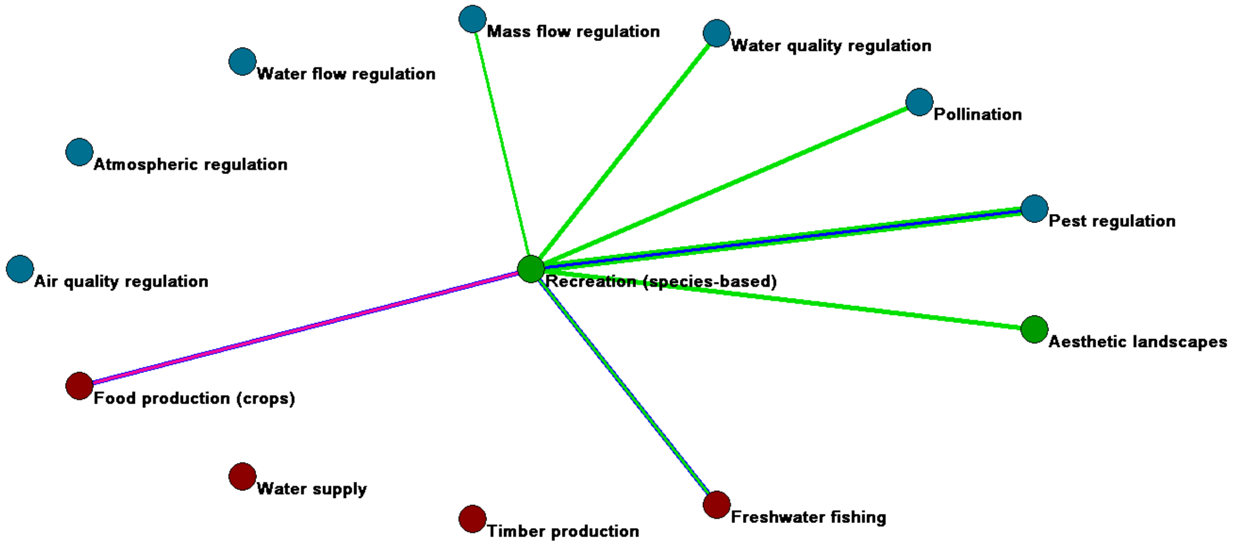

Figure 46). There are positive links to aesthetic landscapes, water quality, freshwater fishing, pest regulation (through hunting of nuisance animals such as feral pigs, and the protection of pest predators such as bats and dragonflies) and pollination (by bats). There are some negative links to food production, due to the impact of agricultural water pollution on marine wildlife.

Figure 28

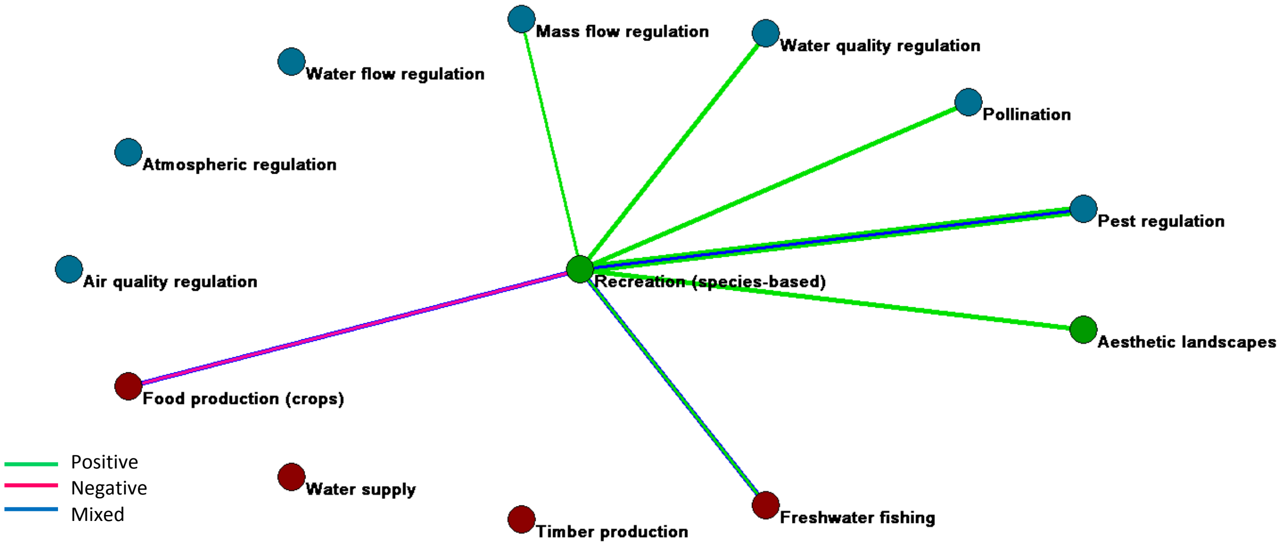

Figure 46: Interactions between species-based recreation and other ecosystem services (unclear interactions and those identified in reviews of the other services are omitted). Line thickness is proportional to number of studies citing the interaction.

4.13 Aesthetic landscapes

Almost all studies consist of surveys of individual preferences for different landscapes, often using photographs, and almost all are located in Europe or North America. The most common indicators are

scores or rankings for perceived aesthetic value or scenic beauty. In all studies, the provider is the entire habitat (community is less relevant for this service), such as a woodland, ornamental park or mixed rural landscape (Figure 47).

The effect of biotic attributes is predominantly positive, with community-level attributes most often cited. The presence of a particular habitat is cited 30 times, with forests and water features being most often mentioned. There is evidence that people value urban trees and green space (e.g. Kaplan, 2007). Proximity of forests and parks has a significant positive effect on housing prices and households are willing to pay to enlarge nature areas. Habitat structure is the most frequently cited attribute, appearing in 47 of the 60 studies, with the term 'structure' being interpreted as covering a broad range of characteristics including landscape diversity and complexity, vegetation density, naturalness and uniqueness. (For this ecosystem service, the attribute of 'landscape diversity' is often included under 'community/habitat structure'). Many studies find a preference for wilder, more complex, more natural landscapes (e.g. Acar and Sakici, 2008; Heyman, 2012; Daniel et al., 2012). However, the review finds important differences between cultural groups. Farmers and certain ethnic groups may prefer a more open, managed landscape whereas most user groups tend to prefer a more natural landscape. Some studies also find that people in developed countries tend to appreciate natural landscapes, but some groups originating from other countries (e.g. black Americans or Islamic immigrants) appear to prefer less dense vegetation and more open landscapes, with man-made elements.

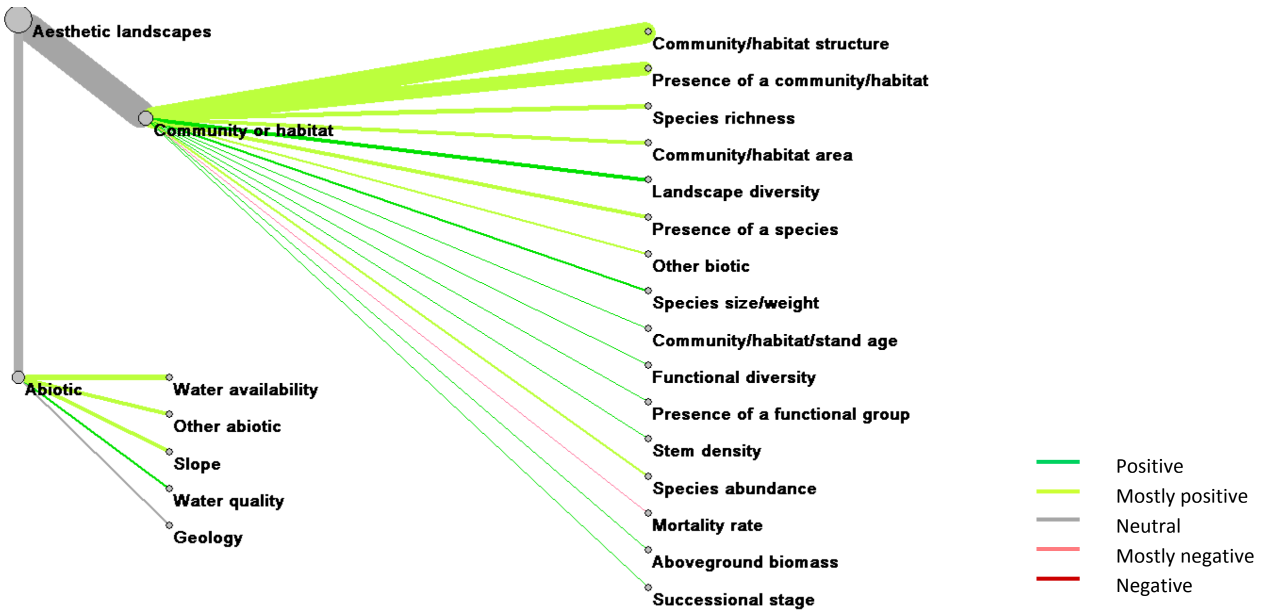

Figure 47: Network diagram showing linkages between ESPs, biotic attributes and abiotic factors for the service of aesthetic landscapes. Line thickness indicates the number of studies showing a given link.

Species-level attributes are mentioned in 13 studies. Most people appreciate the presence of a rich variety of species, and the presence of rare or remarkable species, such as sea turtles in Barbados (Schuhmann et al., 2013). Other biotic attributes cited in the literature include subjective aspects such as a feeling of 'naturalness' or presence of ancestral spirits.

A range of abiotic factors also appear to affect landscape aesthetics including slope, water availability, geology (relief), and water quality. Ten studies cite positive effects from water availability (i.e. the presence of water features), and three found that poor water quality has a negative effect on aesthetic value. There was also a general appreciation of mountainous areas and varied topography (slope and geology).

Human intervention in the form of deforestation, intensive agriculture and built infrastructure (roads, car parks and large buildings) is generally ranked as a negative impact (16 studies). However, positive appreciation for human influences on the landscape was found in six studies, including traditional agriculture, cultural buildings and hiking trails for access.

Few clear interactions with other ecosystem services were identified in this review (Figure 48). There are mixed links with food production, depending on the reaction of different groups of people to different types of agricultural landscape. Figure 28 Timber production is positively correlated to aesthetic value once, in a study where forestry was considered to be part of local cultural heritage, though there are seven unclear correlations (not shown). Some studies identified synergies with water quality regulation and recreation.

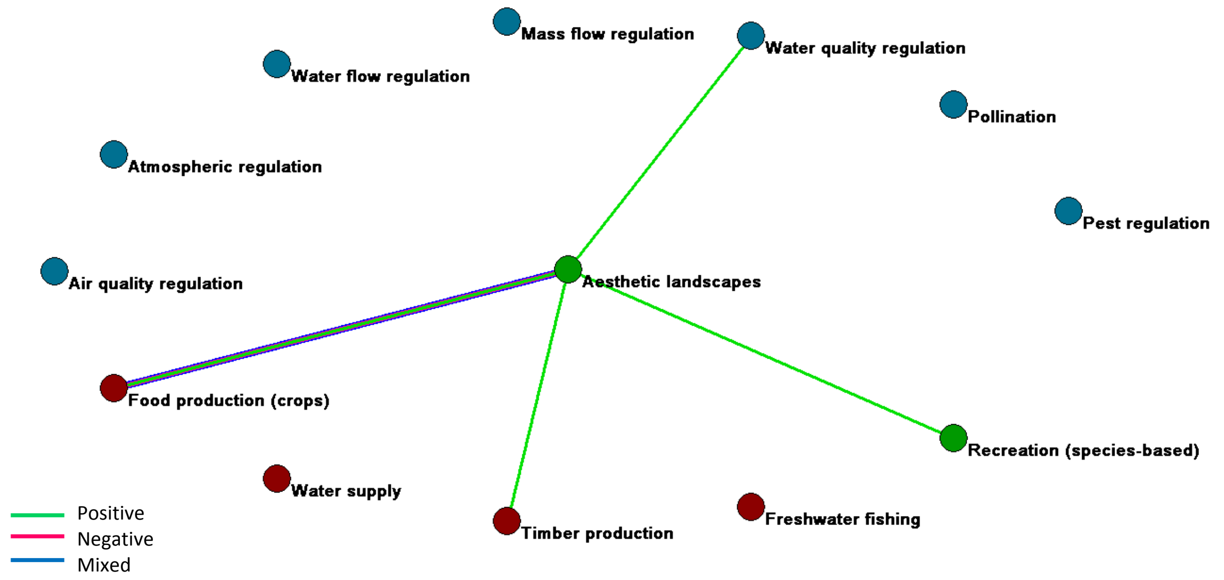

Figure 48: Interactions between aesthetic landscapes and other ecosystem services (unclear interactions and those identified in reviews of the other services are omitted). Line thickness is proportional to number of studies citing the interaction.

5 Discussion

This review of 780 journal articles represents a thorough investigation of the current state of the literature on the links between natural capital and ecosystem services. The review has collected a large amount of useful data, but has also revealed significant gaps in the literature.

5.1 Coverage of regions and ecosystems

There seems to be a significant bias in the geographical coverage, with 58% of the study sites identified in the literature review being located in Europe and North America. Only 7% are in Africa, 16% in Asia, 8% in Oceania and 4% in South America. This might be partly related to the focus on journal articles written in English but, given the importance of natural capital in underpinning essential ecosystem services worldwide, it does seem to indicate a need for a wider geographical spread of research locations. Although there is no indication of a major variation in the influence of biotic attributes across continents, there are certainly examples that illustrate the importance of local factors when evaluating ecosystem service provision. For example, forest plantations seem to have a predominantly negative effect on water supply in hot, dry climates such as Australia, but cloud forests in South America have a beneficial impact on water supply.

The literature reviewed covered a reasonably broad spread of ecosystems, dominated by forests (30%), cropland (20%) and grassland (14%), followed by urban (9%), rivers and lakes (9%) and wetlands (8%). Though some ecosystems were discussed very rarely, this does not necessarily indicate a research gap: it may be partly due to a lower level of ecosystem service provision by some categories such as sparsely vegetated land, and partly to the choice of services for this review, which accounts for the low number of studies addressing marine ecosystems.

Although the Millennium Ecosystem Assessment (MA, 2005) found that the widespread degradation of natural capital poses a serious threat to human wellbeing, there was very little information on the condition of ecosystems and how this affects their ability to provide ecosystem services. In particular, there is very little information on the existence of thresholds beyond which further loss of natural capital would severely compromise ecosystem functioning and service delivery. Even the additional search using the term “threshold” failed to find a significant body of research in this area. The thresholds identified by the review focused mainly on a limited number of services such as food production, air and water quality regulation and water supply. Thresholds relating to other services including timber production, atmospheric regulation, freshwater fishing, aesthetic landscapes, pest regulation and pollination seem to be rarely examined. However, the limited information found clearly demonstrates the potential importance of this issue. For example, Nosetto et al. (2005) suggest that deforestation above a threshold of 20% would begin to significantly affect cloud cover in the Amazon Basin, thus reducing the provision of freshwater. This is clearly an area where more research is needed.

5.2 Linkages between natural capital and ecosystem services

The review shows that the literature directly addressing linkages between natural capital, ecosystem function and ecosystem services is quite limited. Relatively few articles were found that explicitly identify ecosystem service providers and the ways in which biotic and abiotic attributes affect ecosystem service provision. Indeed, as the concept of “ecosystem services” is relatively new, many articles did not use terms such as “ecosystem service provider” or “biotic attribute”, and the reviewer used their own judgement to identify the provider and to infer links to attributes. This lack of ecosystem service-related terminology in the literature also led to the possibility of alternative interpretations by different reviewers. For example, for an article examining three different species of pollinating insects, one reviewer might classify the ecosystem service provider as being “multiple species” and another might classify it as representing the

"functional group" of pollinators. To minimise these effects, a quality control check was undertaken on the final database by a single researcher. However, it is still important not to over-interpret apparent differences between ecosystem services in the database.

Despite these data gaps, and the possibility of minor inconsistencies in the database, a number of robust conclusions have emerged from the review. Firstly, it is very clear that most of the biotic attributes identified in the review have a beneficial impact on ecosystem service provision. The main exceptions are mortality rate; the impact of non-native species; the impact of plantations on water supply; and a limited number of examples where monocultures provide a better service than polycultures (e.g. in eight of the studies on timber plantations).

Many studies look only at the entire area of a habitat such as forest or wetland, or the abundance of a particular species or functional group. Other biotic attributes are rarely studied, and these often have to be inferred by the reviewer rather than being explicitly mentioned. Nevertheless, it is possible to identify several distinct clusters of attributes that provide ecosystem services in different ways.

The most commonly identified cluster of attributes relates to the physical amount of vegetation within an ecosystem: habitat area, primary productivity, above- and below-ground biomass, stem density, species size/weight, growth rate, and successional stage. These tend to have beneficial impacts on a particular group of services: atmospheric regulation, water flow regulation, mass flow regulation, water quality regulation and air quality regulation. The reasons for this are fairly obvious. For atmospheric regulation, the amount of carbon stored in an ecosystem is directly proportional to biomass, so larger and older trees provide a better service. For water flow regulation, trees intercept rainwater and absorb groundwater through evapo-transpiration, and coastal vegetation provides a physical barrier to storm waves and tsunamis. For mass flow regulation, vegetation roots stabilize soil and thus prevent erosion, especially on steep slopes, and for water quality regulation the area of vegetated land, especially forests or wetlands, is important for filtering water, absorbing excess nitrogen and preventing runoff of polluted water into streams. For air quality regulation the leaves of trees and bushes trap and absorb pollution. The major exception was for water supply, where this cluster of attributes can have a negative effect, with 41 studies finding that forests can reduce stream flows downstream. However, this depends on the type of forest and the local hydrology: the negative effects are mainly related to plantations of fast-growing species such as pine and eucalyptus in dry climates, but there are also 15 positive examples where cloud forests capture moisture from the air, and natural forests improve groundwater infiltration.

The second cluster focuses on the presence or abundance of particular species or functional groups. This is particularly important for the provision of freshwater fishing, timber, species-based recreation, pollination and pest regulation. Again, the reasons are fairly obvious as these services rely on the existence of commercially important species of fish and timber, species of interest to eco-tourists, and species or functional groups of pollinating insects such as bees, or pest predators such as wasps or hoverflies. A number of species-specific traits are significant in determining which species are most effective for the provision of certain services, especially species size (for species-based recreation and fishing), and behaviour for pest predators and pollinators.

Although articles discussing other biotic attributes are less common, there is a growing body of research into the effect of a cluster of diversity-related indicators. These include species richness, species population

diversity, functional richness and functional diversity, but also structural complexity and landscape diversity. These studies illustrate the two classic mechanisms through which diversity can contribute to ecosystem services. The first is niche complementarity, where efficiency is maximised because different organisms occupy different ecological niches. For example, carbon storage can be greater in a forest where a mixture of different trees and shrubs with a range of heights and root depths maximises use of the available light, water and nutrients. The second mechanism is the selection effect, where the presence of a wide range of different species improves the chance that one of them will be a high performer, such as a large species of tree (good for carbon storage) or a particularly effective pest predator. Interestingly, both of these mechanisms are shown to be important in different circumstances, sometimes for the same ecosystem service (see the reports on atmospheric regulation and water quality regulation in Annex 5). Surprisingly few articles mention the role of diversity in underpinning the resilience of the ecosystem to environmental change, but this was not a major focus when selecting the search terms for the literature review. It is possible that more literature could be identified using a specific search including the term “resilience”.

Because diversity can lead to more biologically productive ecosystems, it tends to benefit services that depend on the physical amount of biomass, especially timber and food production, freshwater fishing, atmospheric regulation, mass flow regulation and water quality regulation. However, there is a separate group of services that benefit from diversity itself, regardless of its impact on productivity. Pollination and pest regulation services are greatly enhanced by the existence of a community consisting of a variety of species that can pollinate different flower shapes and sizes, prey on different species, or are active at different seasons or different times of day. Diversity also benefits species-based recreation where, for example, eco-tourists like to see a wide variety of wildlife.

At the landscape level, habitat diversity is also of great importance for maintaining effective populations of pollinators and pest predators close to cultivated crops, as these organisms depend on natural or semi-natural habitats to provide alternative sources of food and shelter when crops are harvested. Structural diversity and complexity is also important to provide a variety of feeding, breeding and over-wintering sites for beneficial insects, and also improves landscape aesthetics, atmospheric regulation, water quality regulation and water flow regulation.

Abiotic factors also affect the delivery of ecosystem services, but the impact varies depending on the context, with examples of both positive and negative effects as well as a large number of studies where the direction of the impact is unclear. The comment fields in the review database were important for this analysis, as it is not possible to assign a consistent direction of impact to a factor such as “soil” or “geology”. These comment fields also reveal differences of approach between reviewers, with some reviewers recording every mention of an abiotic factor (contributing to the large number of “unclear” studies) whereas others recorded only cases where the factor was shown to affect the ability of the ecosystem to deliver the service.

The review showed that ecosystems are vulnerable to climatic factors such as precipitation and temperature. Exposure to conditions outside a given range can diminish their ability to provide ecosystem services. The analysis of abiotic factors is therefore useful to help to predict how the delivery of ecosystem services might be affected by future environmental change. In particular, a number of studies cite examples of how climate change could impair the delivery of ecosystem services in the future. Food production is

known to be vulnerable, as crop yields could be reduced due to higher temperatures, reduced water availability and desertification. Higher temperatures can also increase fish mortality, increase emissions of volatile organic compounds from vegetation, degrade coral reefs (which provide flood protection), cause more forest fires (thus releasing carbon into the atmosphere) and increase algal blooms (bad for water quality and fishing). Rising sea levels, linked to global warming, can inundate wetlands, leading to loss of water flow and water quality regulation services. Droughts (recorded as decreased water availability or precipitation) can dry out wetlands, leading to loss of services including atmospheric regulation, and they can also damage the ability of trees to provide carbon storage and air quality regulation. Higher temperatures are also linked to more evaporation of ground and surface water, leading to reduced water supply especially when this increases the salinity of groundwater supplies, and to reduced snow cover, decreasing the supply of freshwater from meltwater. However there were isolated examples of benefits from climate change, including increased crop and timber production and carbon storage due to enhanced plant growth at higher altitudes or more northern latitudes (i.e. in what were formerly colder climates), and a CO_2 fertilisation effect that could boost crop yields in some cases.

In view of the likely increase in extreme weather events as a result of climate change, it is interesting to note the discussion in the water flow regulation report (Annex 5). A number of studies appear to show that the ability of forests to provide flood protection decreases, eventually to zero, for more extreme rainfall events. However, more recent work queries this interpretation of the data and claims that forests reduce both the frequency of floods of a certain size, and the size of downstream peak flows, for all rainfall events.

In some studies, it appears that ecosystems deliver greater benefits in more testing circumstances. For example, the benefits of vegetation in stabilising soil appear to be greater on steeper slopes (Mandal et al., 2013), and wetland vegetation absorbs more excess nitrogen when concentrations in the water are higher (Christen and Dalgaard, 2013).

5.3 The role of human intervention in protecting and enhancing ecosystem services

Human activities are shown to have a range of positive and negative impacts, and many studies cite a mix of both. Although ecosystems are suffering widespread degradation from activities such as intensive agriculture, deforestation and urban development, there are also many examples of ways in which ecosystem services can be enhanced through protection, restoration and sustainable management of ecosystems. For example, organic agriculture can be beneficial for pollination and pest regulation; forests can be planted to provide mass flow regulation; and wetland restoration can improve water quality regulation. There are also examples of trade-offs and negative feedbacks within services, such as the potential damage and disturbance to wildlife caused by excessive eco-tourism activities, though there are opportunities to minimise this through careful regulation and sustainable management.

The role of human intervention is particularly important because of the significant level of interactions between ecosystem services. Interactions are identified in 45% of studies, though these are not always investigated explicitly. The majority of interactions (64%) are positive, highlighting the fact that many ecosystems have multiple benefits. For example, forests can provide atmospheric regulation, water flow regulation, mass flow regulation and aesthetic benefits. However, there are also some important trade-offs between services, especially between provisioning services and regulating or cultural services.

Management that benefits one service often has negative impacts on another. Commonly cited examples include fertiliser application, which benefits food and timber production, but has negative impacts on water quality and freshwater fishing. Similarly, harvesting forests for timber has a negative impact on atmospheric regulation, water flow regulation and (for clear-cutting) aesthetic landscapes. Sometimes management has short-term benefits, but may have adverse consequences in the long-term. For example, intensive farming may produce high crop yields but it could also cause a long-term decline in populations of pollinators and pest predators, threatening future food security. Improved analysis of these interactions could help decision-makers to develop management strategies that exploit synergies and balance trade-offs more effectively.

6 Conclusions

6.1 Outputs for OpenNESS

This review has synthesised a large and varied mass of literature into a single database with a simple and logical structure, enabling a detailed analysis of the way in which natural capital stocks (both biotic and abiotic) contribute to ecosystem service flows.

This knowledge base can now be used to improve the design and selection of data for the ecosystem service mapping and modelling methods being developed and applied within the OpenNESS case studies (Task 3.2), and the accompanying guidance being developed to assist the case studies (Task 3.4). A refined version of these tools, datasets and guidance will form part of the Oppla web-platform (www.oppla.eu) to make them accessible for future application by the wider user community (Work Package 6).

Useful outputs of the database and analysis for the rest of the OpenNESS project include:

- A simple and effective typology for classifying ecosystem service providers, biotic and abiotic attributes and the links and interactions between them;
- A useful set of indicators of ecosystem service supply, which can now be refined from the original JRC indicator list as a result of this exercise;
- Information on the contribution of different ecosystems and land cover types to different ecosystem services;
- Identification of the multiple benefits and synergies provided by many ecosystems, especially forests, which contribute to all 13 ecosystem services investigated here;
- Identification of potential negative impacts, interactions and trade-offs between and within ecosystem services;
- Information on the mechanisms by which natural capital contributes to ecosystem services, including habitat area, species abundance, species traits and the role of functional diversity;
- Information on the way in which abiotic factors affect ecosystem condition and the delivery of ecosystem services, especially concerning the threat posed by future climate change;
- Preliminary indication of the importance of thresholds for ecosystem service supply, e.g. percentage of forest area in a catchment required to deliver flood protection or meet water quality standards;
- Examples of ways in which human activities can improve or protect ecosystem service delivery;
- Awareness of areas where data is lacking, which can be used to guide future research (see below).

The review emphasises the importance of conserving biodiversity and natural capital in order to continue to deliver robust and resilient ecosystem services in a changing world. It also provides valuable information on the effectiveness of different species, habitats and management techniques – for example, the selection of wetland species for excess nutrient removal, the value of old-growth forests for carbon storage, or the establishment of semi-natural habitats around crops to boost populations of beneficial insects.

Using this information base, local decision-makers can identify opportunities to protect and enhance vital ecosystem services in their area, maximising synergies and minimising trade-offs between services, whilst national and regional policy-makers can design effective policies to facilitate these goals at a wider scale. The need for careful policy design is particularly urgent in order to balance trade-offs between provisioning and regulating or cultural services, and to protect ecosystems against future climate change and urban development. To preserve a balanced mix of ecosystem services as well as a healthy underlying level of biodiversity to sustain future services, it will be necessary to protect certain key habitats such as wetlands and old-growth forests from over-exploitation.

6.2 Data gaps and recommendations for future work

As discussed above, the review identified a number of gaps in the literature concerning the relationship between natural capital and ecosystem services. To address the needs of decision-makers, future research should aim to:

- Extend geographical coverage to include more studies relevant to Africa, Asia, South America and Oceania;
- Address the link between biodiversity and ecosystem services more explicitly, especially through studies that examine the role of functional diversity in delivering services and providing resilience to change;
- Examine the impact of ecosystem condition on ecosystem service provision;
- Investigate potential thresholds in the biophysical state of ecosystems, beyond which the future delivery of ecosystem services could be compromised;
- Study interactions between ecosystem services, including synergies and trade-offs and the implications for decision-makers, for example with respect to land use management, or options to minimise negative interactions such as pollution or over-exploitation of resources ;
- Evaluate ways in which human management and related policies can protect and enhance ecosystem services and build resilience to change.

Finally, the review yielded a number of useful recommendations for improvements to the OpenNESS literature review methodology. These have been summarised in an internal project document which is available on request. They include potential enhancements to the database and additional guidance for reviewers to improve the consistency of the literature review. One major area for improvement relates to the choice of indicators, as it is clear that the JRC indicators for mapping ecosystem services (Egoh et al., 2012) did not adequately cover all of the ecosystem services reviewed, especially for the services freshwater fishing, food provision, and mass flow regulation. Some of the services failed to cite any of the indicators found in the JRC review, and a number of important additional indicators were identified which could be included in future work.

Annex 1: Supplementary literature search on ecosystem services and biophysical thresholds

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The literature review presented in this deliverable included examination of how selected studies address the possible existence of thresholds. Reviewers collected information on legal boundaries, safe minimum standards and biophysical thresholds. Only 63 studies (out of 709) explicitly mentioned the existence of thresholds for specific ecosystem services (some studies mentioned more than one threshold, so 68 thresholds were identified in total). Of these, 50 studies addressed biophysical thresholds (53 thresholds). Two-thirds of these address ecosystem services related to water: 17 investigated water supply, nine investigated water quality regulation, and five investigated water flow regulation (flood protection). Biophysical thresholds were also mentioned in eight studies on food production, and between one and three examples were found for each of the other nine services reviewed.

Biophysical thresholds pertaining to ecosystem service delivery are a topic of great interest because their existence essentially defines the limits for sustainable use of natural capital. Thresholds are a subcategory of many non-linear relationships that are common within ecological systems. The simplest definition of a threshold or discontinuity is a rapid state change occurring as a consequence of a smooth and continuous change in an independent variable (Luck, 2005). In the context of resource use and management, thresholds are often associated with *tipping points* and their subsequent *regime shifts*: concepts that involve large abrupt and persistent changes in the structure and function of a system (Biggs, 2009). There is a vast literature on the presence and dynamics of thresholds in ecology and socio-ecological systems, and thus we reasoned that the 50 articles found in the main literature review were only a very small subset of the articles in the literature that addressed how thresholds in a system's biophysical attributes influence ecosystem service delivery.

To determine the information available in the existing scientific literature regarding threshold relationships between an ecosystems' biophysical attributes and the ecosystem services they provide, a supplementary search of articles included in the ISI web of science online database was conducted, using "ecosystem AND service AND threshold" as subject search terms. These search criteria resulted in 264 articles. The abstracts of these articles was first examined and then the main text to ascertain whether these articles revealed any relevant information; this resulted in 80 articles which treated the concept of thresholds in a way that was relevant to ecosystem services and natural capital. It was never intended that this simplistic search would produce an exhaustive list of all instances in the literature where researchers pursued questions pertaining to biophysical thresholds and ecosystem processes and functions. The initial result (264 hits) is a full order of magnitude lower than the results found using "ecological AND threshold" as subject search terms (2948 hits). Furthermore, a search using "ecosystem AND threshold" yielded even a greater number: 3254 hits.

Even though there is a vast literature on ecological thresholds, little has been connected to ecosystem services as yet. Nevertheless, the thresholds addressed in these thousands of articles have almost certain relevancy in the context of ecosystem services, even if the authors did not address ecosystem services explicitly. "Ecosystem service" is also a recently coined term (Braat and De Groot, 2012), and this is reflected in the publication dates of the articles identified in our supplementary review. With the exception

of Carpenter et al. (1999), all articles were published within the past 10 years (Figure 1). The most comprehensive effort to date connecting the broader literature on thresholds with ecosystem service delivery is a database maintained by The Resilience Alliance titled “Thresholds and Regime Shifts in Ecological and Social-Ecological Systems” (Resilience Alliance and Santa Fe Institute, 2004). Presently the database includes 278 references which address 103 examples of thresholds which all have relevance to ecosystem service delivery. The examples are also categorised according to whether a state change has occurred (demonstrated) or is merely proposed.

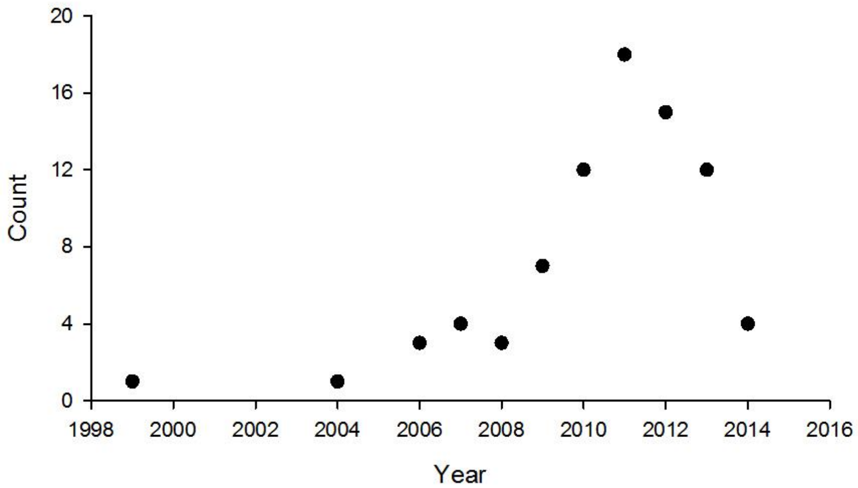


Figure 1: Publication dates for the 80 articles reviewed for addressing biophysical thresholds relevant to ecosystem service provision.

It is also noteworthy that only one article found through the “ecosystem AND service AND threshold” ISI search was among the 50 articles identified through the main literature review. One possible explanation for this discrepancy is that the search terms used in the supplementary review are more restrictive than the criteria reviewers used for identifying biophysical thresholds in the main reveiw. “Threshold” is often used interchangeably with “limit”, even though the two terms are not completely synonymous (a threshold is a type of limit, but not all limits can be considered thresholds according to the definition provided earlier). An ISI search that used “ecosystem AND service AND limit” yielded 1136 results. The 50 articles identified in the main review may have either addressed biophysical limits that could also be thresholds without the articles’ authors referring to them as thresholds, or the use of the word “threshold” could have been buried in the manuscript sufficiently that it was undetectable by the ISI search engine.

Only 28 of the articles reviewed in this supplementary search represented original research that attempted to quantify or otherwise assess thresholds that pertained to either biophysical attributes or the associated ecosystem services. Many articles addressed thresholds and ecosystem services either by alluding to the possible or probable existence of thresholds in specific systems, by identifying them as a component of dynamics in a modelled system outside of the context of specific services, or by calling for increased research that would be capable of identifying real-world thresholds. The remaining articles (26) were review or concepts articles that referenced data from previous studies that identified thresholds. Quantifying the number of articles referenced in these review articles was outside of the scope of this effort, but very few cited articles that had also turned up in our supplementary search were found,

indicating that the cited research regarding a given biophysical threshold did not explicitly utilise “ecosystem services” as a term.

The 28 articles that attempted to quantify thresholds focused on an array of ecosystem types: rangeland and grasslands (6 articles), agro-ecosystems (4), rivers/streams/wetlands (4), marine (3), urban (3), estuarine (2), alpine (2), and various additional terrestrial ecosystems. Studies were located on all continents, with focal areas ranging from small plots of unspecified size at a single field station to areas greater than 350,000 km^2. The biophysical attributes were also quite varied, with landscape complexity or fragmentation being the only attribute found in more than one article. The drivers affecting the attributes were less varied. Land use and management, overharvesting, overgrazing, urbanisation and development were identified as the drivers. Only two articles identified climate change as moving biophysical attributes towards or past a threshold, and only one article cited invasive species.

Of the articles that are able to identify threshold values for the biophysical attributes, many provide evidence that the systems have either partially or fully passed a threshold. Two articles indicate that thresholds have already been passed, and 12 describe heterogeneous systems where thresholds have been passed in some places but not others. An additional seven articles provide evidence that their systems are approaching thresholds.

Annex 2: Analysis of variation of biotic attributes by location and spatial scale

Analysis of whether biotic attributes vary depending on spatial scale and location is limited by the small number of database entries for the larger scales, which creates a bias. For example, 42 studies on mass flow regulation are at the local scale, with only one each at continental or sub-continental scale and three each at national or sub-national scale. Due to the larger number of studies at small scales, it is more likely that a large range of attributes and ESPs have been recorded by reviewers, whereas for larger scales the substantially lower number of studies entered into the database means it is less likely that such a large range of attributes and ESPs have been recorded.

Despite this limitation, one difference between spatial scales is apparent (though perhaps not surprising): studies at large scales (i.e. global, continental and national) tend to focus more on entire communities or habitats, and to study community and habitat level attributes. In contrast, local scale studies tend to investigate a broad range of ESPs including specific species and functional groups as well as entire communities/habitats (Figure 1). This is because smaller scale studies (often including field or laboratory experiments) are capable of detailed comparisons of particular species or functional groups, which is more difficult at larger scales.

For example, local and sub-national scale studies of atmospheric regulation investigate carbon storage by specific species populations (e.g. pine plantations), functional groups (e.g. grasses), and entire communities (e.g. comparing pasture and forest). However, at the national and global scales, only forest - a single community/habitat - is considered in the literature reviewed. This tendency for communities to be the only ESP at larger scales applies to most of the ecosystem services, so it is likely that this is not simply an artefact of the low number of studies at large scales. The main exceptions to this are for food provision, freshwater fishing and pollination, where the focus at all scales is on specific species populations, i.e. different food crops, fish species or pollinating insects, or, for pollination, functional groups (e.g. flower-visiting insects). Figure 2 shows the distribution of ESP by spatial scale with these three species-oriented services omitted: the tendency for larger scales to focus more on the community as ESP is more pronounced.

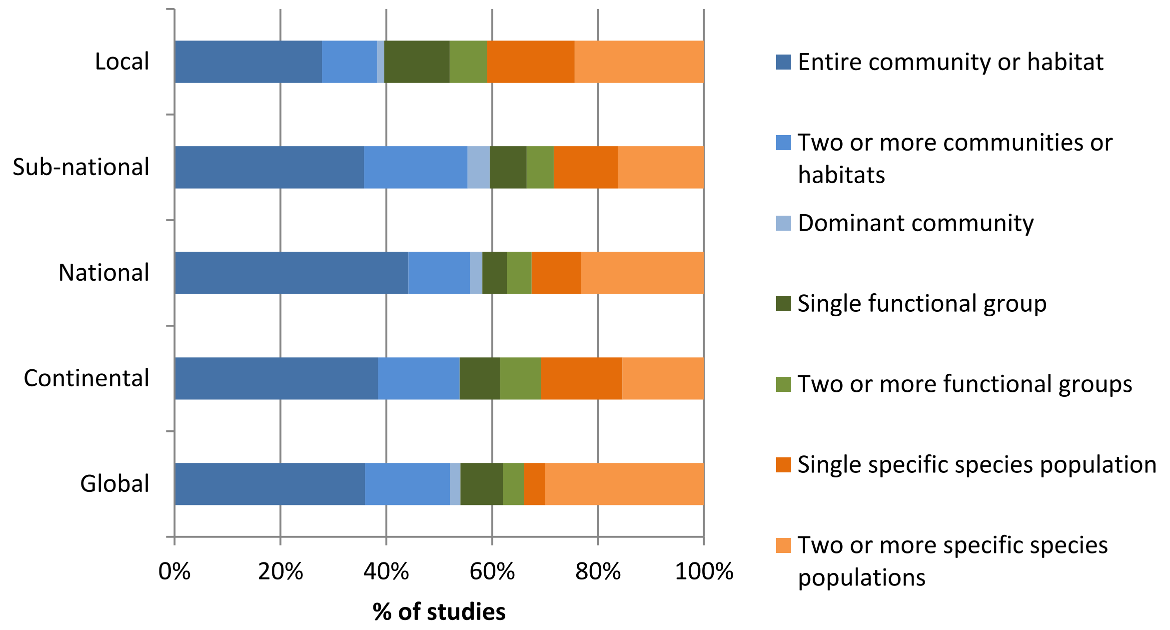


Figure 1: ESP by spatial scale (continental and sub-continental scales are combined due to the small number of entries at sub-continental scale)

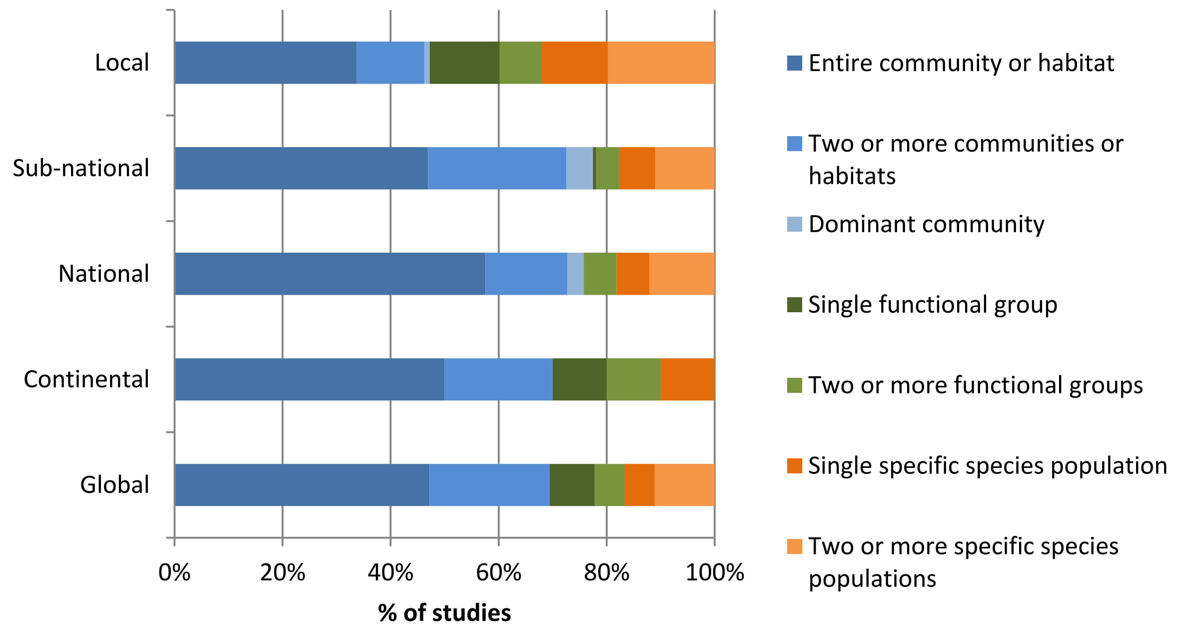


Figure 2: ESP by spatial scale with food production, freshwater fishing and pollination omitted (continental and sub-continental scales are combined due to the small number of entries at sub-continental scale)

To analyse whether biotic attributes are linked to spatial scale or location, a simplified dataset was compiled (Table 1) by combining the continental and sub-continental scales, both of which were sparsely populated; removing the "other" category; deleting sparsely populated categories (sapwood; leaf N content); and combining similar attributes into the following attribute clusters:

Biomass
- aboveground biomass
- belowground biomass
- productivity
- wood density

Community/habitat area
- presence of a specific community/habitat type
- community/habitat area

Community age / successional stage
- community/habitat age
- successional stage

Diversity
- species richness
- functional richness
- functional diversity
- species population diversity

Species or functional group abundance
- presence of a specific species
- abundance of a specific species
- abundance of a specific functional group
- presence of a specific functional group

Visual inspection of Table 1, in which the most commonly cited attributes are shaded in darker shades of green, does not reveal any obvious variation in the frequency distribution of biotic attributes by spatial scale. This is confirmed when the results are plotted graphically, as shown in Figure 3.

Table 1: Simplified table showing number of studies mentioning biotic attributes vs. spatial scale, for all ecosystem services combined.

	Local	Sub-national	National	Continental	Global	Total
Community/habitat area	180	105	18	7	23	**333**
Community/habitat structure	82	73	11	5	13	**184**
Community age/successional stage	49	30	2	1	4	**86**
Litter/crop residue quality	16	4			1	**21**
Biomass	88	32	7	2	8	**137**
Stem density	17	6	2		1	**26**
Mortality rate	15	7	2	2	4	**30**
Species/functional group abundance	212	82	17	1	26	**338**
Species size/weight	49	15	2	3	7	**76**
Population growth rate	9	7		1	2	**19**
Flower-visiting behavioural traits	11	4	1		3	**19**
Predator behavioural traits	9	2			3	**14**
Life span/longevity	5	1	1		4	**11**
Diversity	140	70	20	1	20	**251**
Landscape diversity	9	6			3	**18**
Total	**891**	**444**	**83**	**23**	**122**	**1563**

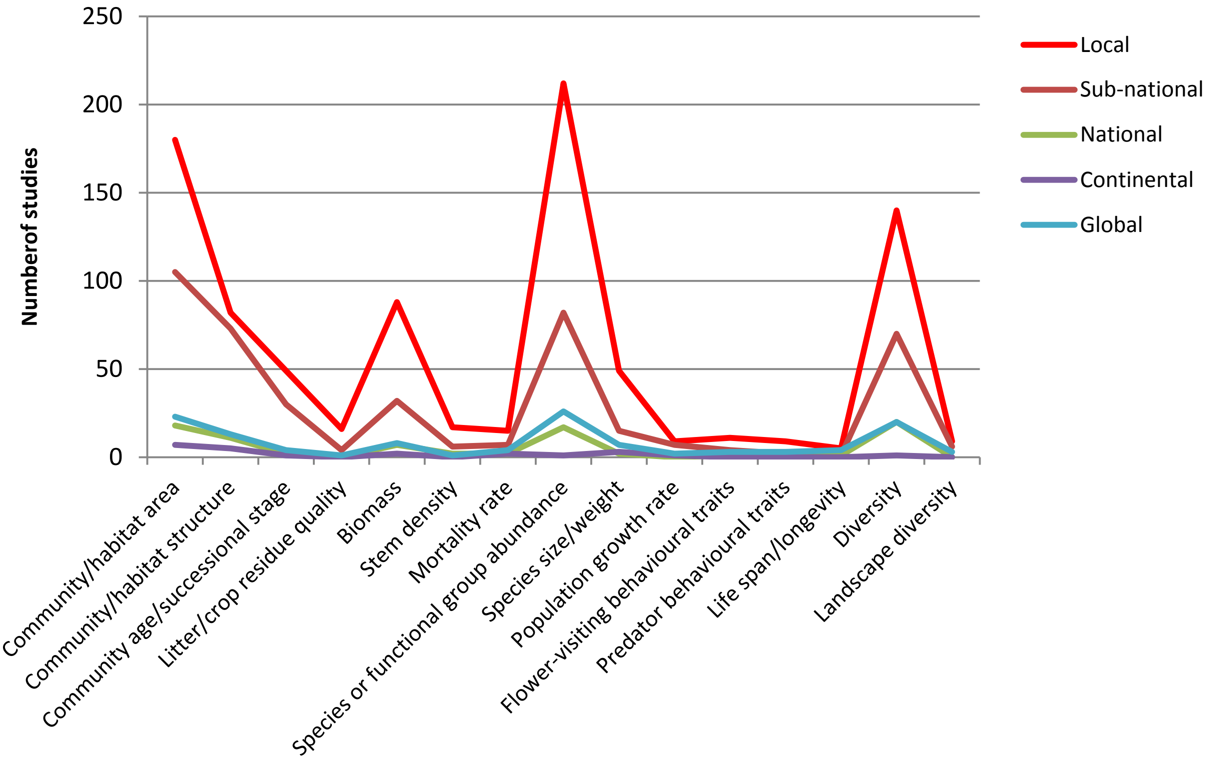


Figure 3: Line graph showing frequency of citation of biotic attributes for each spatial scale.

Similarly, there is no apparent variation in the pattern of biotic attributes between studies located in different continents (Table 2; Figure 4).

Table 2: Simplified table showing number of studies mentioning biotic attributes vs. continent, for all ecosystem services combined.

Row Labels	Europe	North America	South America	Africa	Asia	Oceania	Global	Total
Community/habitat area	113	82	18	9	58	30	23	**333**
Community/habitat structure	72	33	10	10	29	17	13	**184**
Community age/successional stage	17	19	10	2	16	18	4	**86**
Litter/crop residue quality	8	2	1	2	3	4	1	**21**
Biomass	31	44	5	10	31	8	8	**137**
Stem density	6	9	2		2	6	1	**26**
Mortality rate	5	10	3		7	1	4	**30**
Species/functional group abundance	97	96	16	26	56	21	26	**338**
Species size/weight	10	23	7	7	18	4	7	**76**
Population growth rate	4	3		1	7	2	2	**19**
Flower-visiting behavioural traits	5	5		2	2	2	3	**19**
Predator behavioural traits	7	1			3		3	**14**
Life span/longevity	3	4					4	**11**
Diversity	77	80	8	21	33	12	20	**251**
Landscape diversity	5	4		2	3	1	3	**18**
Total	**460**	**415**	**80**	**92**	**268**	**126**	**122**	**1563**

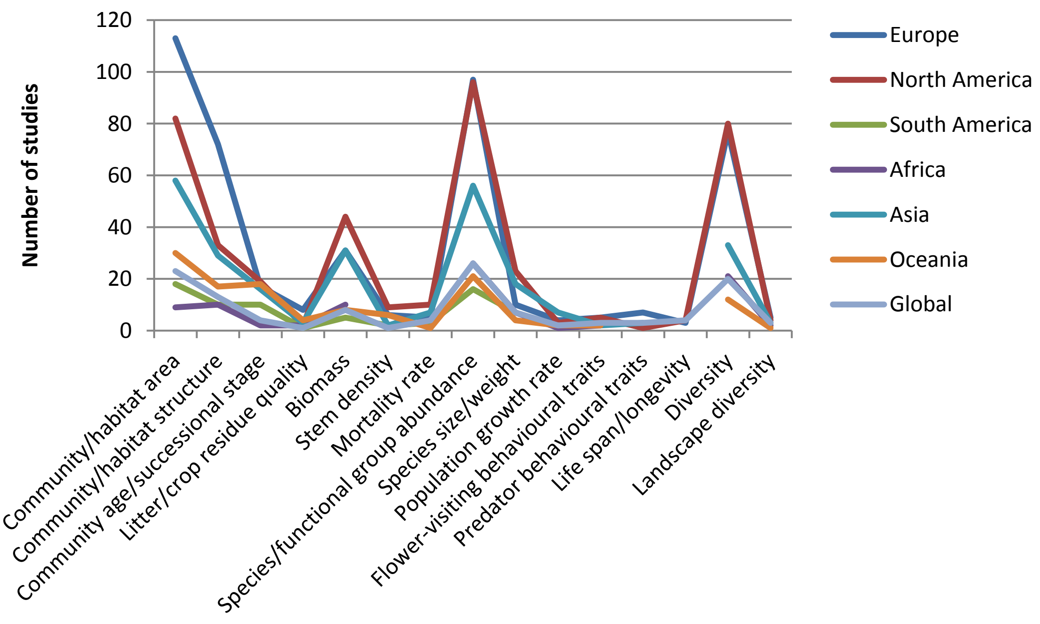


Figure 4: Line graph showing frequency of citation of biotic attributes for studies located on each continent.

Annex 3: Indicators for ecosystem assessment

The majority of the ecosystem service literature reviewed (88%) used assessment methods which were based on primary data, such as direct field observations or public statistical databases. Mechanistic, correlative and conceptual models were used very rarely (Figure 1).

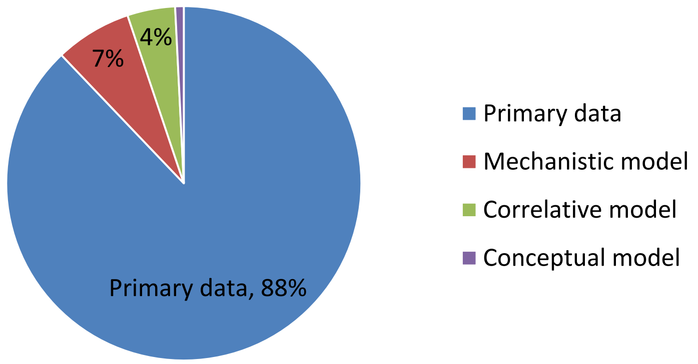


Figure 1: A breakdown of the assessment methods used in the studies reviewed.

Only 87% of the studies recorded indicators, and 36% discussed an indicator which had not been identified previously by the JRC review on indicators for mapping ecosystem services (Egoh et al., 2012), as shown by the significant number of entries labelled "other" in Table 1. While the JRC indicators were useful for some services such as atmospheric regulation, they were not relevant for research on freshwater fishing, where there was no mention of either of the two JRC indicators (water supply or river salinity) in the reviewed literature, but additional indicators (including catch per unit effort) were used in 36 of the 60 articles. For timber production, of the four JRC indicators which had been identified for this service, "timber production" was mentioned in all articles citing indicators, whereas "raw material" was cited only once, and there was no mention of the other two indicators: "fuel wood" or "reeds".

Table 1: JRC indicators for ecosystem assessment cited in the literature for the various ecosystem services.

Ecosystem service	Indicator name	No. of studies	% of studies
Freshwater fishing	Other	36	60%
Timber production	Timber production	60	100%
	Raw material	1	2%
	Other	1	2%
Water supply	Water supply (precipitation)	28	47%
	Water supply	16	27%
	Soil Characteristics	12	20%
	Land cover	11	18%
	Water supply (surface water)	10	17%
	Water supply (ground water)	6	10%
	Litter containment	2	3%

Ecosystem service	Indicator name	No. of studies	% of studies
	Distance to water resources	1	2%
	Other	40	67%
Food production (cultivated crops)	Crop yield	52	87%
	Grain production	42	70%
	Agricultural production	41	68%
	Commodity production value	34	57%
	Fodder provision	6	10%
	Livestock production	2	3%
	Productivity index	2	3%
	Soil productivity	2	3%
	Land cover	1	2%
	Other	19	32%
Air quality regulation	Pollutant concentration	40	67%
	Tree cover	40	67%
	Air purification	33	55%
	Deposition velocity	27	45%
	Other	29	48%
Atmospheric regulation (carbon sequestration)	Carbon storage	43	72%
	Above ground biomass	42	70%
	Soil carbon	35	58%
	Below ground biomass	28	47%
	NPP	15	25%
	Soil Characteristics	15	25%
	Forest biomass	14	23%
	Nutrient flux	7	12%
	Vegetation map	6	10%
	Land cover	5	8%
	Other	6	10%
Mass flow regulation (erosion protection)	Soil erosion	52	87%
	Land cover	43	72%
	Vegetation map	42	70%
	Soil Characteristics	40	67%
	Precipitation	35	58%
	Water retention	27	45%
	Topology	25	42%
	Climate	15	25%
	Land Use	13	22%

Ecosystem service	Indicator name	No. of studies	% of studies
	Litter	8	13%
	Erodibility	4	7%
	Erosion control	4	7%
	Geomorphology	3	5%
	Soil retention	3	5%
	Riparian zone	1	2%
	Other	6	10%
Water flow regulation (flood protection)	Flood attenuation	34	57%
	Hydrological flow	31	52%
	Land cover	15	25%
	Soil Characteristics	8	13%
	Vegetation map	8	13%
	Water holding capacity	8	13%
	Flood prevention	7	12%
	Slope	6	10%
	Annual flood	5	8%
	Digital Elevation Model (DEM)	5	8%
	Water filtration	5	8%
	Water regulation	4	7%
	Flood control	3	5%
	Erosion	2	3%
	Nutrient retention	2	3%
	Water quality	2	3%
	Disturbance prevention	1	2%
	Other	6	10%
Water quality regulation	Water quality	43	72%
	Nutrient retention	37	62%
	Water quality regulation	36	60%
	Vegetation map	10	17%
	Other	5	8%
	Water characteristics	3	5%
	Slope	2	3%
Pollination	Bumblebee density	37	62%
	Land cover	34	57%
	Habitat	27	45%
	Land Use	24	40%
	Crop yield	23	38%

Ecosystem service	Indicator name	No. of studies	% of studies
	Cost of bees	1	2%
	Other	50	83%
Pest regulation	Pest density	18	30%
	Land cover	7	12%
	Pest control (expenses)	3	5%
	Biological control (expenses)	1	2%
	Other	17	28%
Recreation (species-based)	Land cover	5	8%
	Fish abundance	4	7%
	Forest birds density	3	5%
	Forest birds richness	3	5%
	Farmland birds richness	1	2%
	Protected Areas	1	2%
	Other	42	70%
Aesthetic landscapes	Aesthetic value	31	52%
	Scenic beauty	12	20%
	Landscape and nature diversity	6	10%
	Rare species	1	2%
	Other	22	37%

A list of the main additional indicators, i.e. those that appeared in the literature more than once but were not included in the initial list, is provided in Table 2. Many services, especially pollination and species-based recreation, cited a broad range of indicators (41 and 59 additional indicators, respectively); however most of these were cited only once. Those which appear to be particularly important, however, being cited multiple times, include catch/yield for freshwater fishing (10 counts); distance to natural/native vegetation (13 counts) and pollinator visitation rates (17 counts) for pollination; evapotranspiration (14 counts) and water yield (11 counts) for water supply; and visitor numbers for species-based recreation (10 counts).

Table 2: Additional indicators for ecosystem service assessments found in the literature which are cited more than once. Those cited ten times or more have been highlighted in grey.

Ecosystem service	Additional indicators cited in the literature	Frequency
Freshwater fishing	Catch/ yield	10
	Fish size/weight	4
	Catch per unit effort	2
Water supply	Evapotranspiration	14
	Water yield	11
	Stream flow	9
	Catchment/watershed area	3
	Leaf Area Index	3
	Catchment water balance	2
	Plant water use	2
	Sap flux density	2
Food production (cultivated crops)	Soil characteristics	6
	Crop biomass	3
	Water use efficiency	3
	Ecosystem services value	2
	Cost of production	1
Air quality regulation	Greenness	3
	Mixing/boundary layer height	3
	VOC emission factors	3
	BVOC emission factors	2
	Hydrocarbon emissions	2
	Leaf Area Index	2
Pollination	Pollinator visitation rates	17
	Distance to native/natural vegetation	13
	Fruit/seed set	7
	Abundance of bees	6
	Pollinator abundance	6
	Bee diversity	3
	Floral/flower abundance	3
	Floral/flower diversity	3
	Flower density	3
	Pollen grain deposition per visit	3
	Crop type	2
	Floral resource	2
	Hive density	2
	Plant reproductive success	2
	Pollination efficiency	2
Recreation (species-based)	Visitor numbers	10
	Visitor satisfaction	9

Ecosystem service	Additional indicators cited in the literature	Frequency
	Visitor expenditure	6
	Angling/fishing effort	4
	Species abundance	4
	Willingness to pay	4
	Length of trip	3
	Employment	2
	Fledging success (birds)	2
	Frequency of visit	2
	Mortality rate	2
	Recreation/ecotourism opportunities	2
	Travel cost	2
	Travel time (distance to site)	2
Aesthetic landscapes	Willingness to pay	4
	Naturalness	3
	Perception	3
	Property values	3
	Biodiversity	2
	Landscape coherence	2
	Landscape preferences	2

Annex 4: Policies

Only 13% of the studies reviewed cite a particular policy. Some of these cite multiple policies, with 127 examples identified in total by the reviewers (Table 1). Of the 24 EU policies covered in the database, only seven are mentioned in the literature, and these are rarely cited. However, policy is discussed more often than this implies, with many articles describing existing national/local level policies, or discussing policy recommendations in general terms. Policies categorised as “other” occur 89 times in the review. These policies are relatively diverse (a complete list is shown in Table 2). The most commonly mentioned are measures associated with the UNFCCC, such as REDD and the Kyoto Protocol (including Clean Development Mechanism (CDM) schemes) for the service of atmospheric regulation; the RAMSAR Convention on wetlands; and various Biodiversity Action Plans. Policies are cited most frequently for water flow regulation, followed by air quality regulation, atmospheric regulation, food production, pollination, species-based recreation and water supply

Table 1: Counts of policies cited in the literature per ecosystem service.

	Ambient Air Quality directive	Biodiversity Strategy	Common Agriculture Policy	Habitat Directive	Marine Strategy Framework Directive (MSFD)	Soil Thematic Strategy	Water Framework Directive (WFD)	Other	Total
Freshwater fishing	0	0	0	1	1	0	1	4	**7**
Timber production	0	0	0	0	0	0	0	1	**1**
Water supply	0	1	0	1	0	0	0	11	**13**
Food production (crops)	0	0	3	0	0	0	0	6	**9**
Air quality regulation	4	0	0	0	0	0	0	10	**14**
Atmospheric regulation	0	0	0	0	0	0	0	14	**14**
Water flow regulation	0	0	3	4	0	1	5	9	**22**
Mass flow regulation	0	0	1	0	0	1	1	7	**10**
Water quality regulation	0	1	0	1	0	0	4	3	**9**
Pollination	0	1	2	0	0	0	0	11	**14**
Pest regulation	0	0	0	0	0	0	0	1	**1**
Recreation (species-based)	0	0	0	0	0	0	1	10	**11**
Aesthetic landscapes	0	0	0	0	0	0	0	2	**2**
Total	**4**	**3**	**9**	**7**	**1**	**2**	**12**	**89**	**127**

Table 14: Additional policies cited in the literature

Ecosystem Service	Additional policies cited
Freshwater fishing	World Commission on Dams (policy principles and guidelines)
Timber production	None Identified
Water supply	CBD
	CDM (Kyoto, carbon sequestration projects including afforestation and reforestation)
	Integrated Water Resources Management
	IUCN
	National ecological networks (China)
	National Water Acts
	Payment for Watershed Services (discussed)
	RAMSAR Convention
	REDD+
	Soil and water conservation programmes (Otago, New Zealand)
	Spatial Biodiversity Assessments
	Sustainable forest management
	UNFCCC (increased interest in afforestation, e.g. of páramo grassland in the Andes)
Food production (cultivated crops)	Agricultural policies leading to specialisation (Sweden, though subsidiaries, price regulations, legislation and extension)
	Brazil's Proambiente Pilot program (Pecosystem services scheme, Amazonia)
	Food Harvest 2020 Strategy (Ireland; DAFF, 2010)
	Payments for carbon sequestration/ Carbon offsetting
	Subsidies schemes, e.g. for irrigated farming
	RAMSAR Convention
Air quality regulation	City programmes including Barcelona's Energy, Climate Change and Air Quality Plan; NYC million tree planting initiative
	District air quality management plans (US)
	EU specific standards, such as: The Euro Standards on road vehicle emissions; Directive 2010/75/EU on industrial emissions; Directive 94/63/EC on VOCs
	Kyoto Protocol
	National/regional Air Standards (China, US national clear air act, US South Coast)
	Policy to use urban forests to improve air quality (Santiago Regional Metropolitan government, Chile)
Atmospheric regulation (carbon sequestration)	Carpathian Convention
	CDM
	Forest-based carbon offset initiatives
	Kyoto Protocol
	Logging ban policies (China)
	REDD
	Sustainable forest management (SFM) (Ministerial Conferences on the

Ecosystem Service	Additional policies cited
	Protection of Forests in Europe (MCPFE) guidelines)
	UN FAO Forest Resource Assessments
	Urban forestry planning and management (e.g. Hangzhou, China)
Mass flow regulation (erosion protection)	Environmental Law controlling the width of riparian vegetation (Brazil)
	Surface Mining Control and Reclamation Act (North America)
Water flow regulation (flood protection)	Biodiversity Action Plans
	CDM
	Declaration of Arles (to take measures to reduce future flood risks, which include land management and forestry)
	Forestry Stewardship Council timber standards
	Kyoto Protocol
	Ministerial Conferences on the Protection of Forests in Europe (MCPFE) guidelines (for the sustainable management forests)
	Protected forests (e.g. headwaters water resource conservation, Taiwan)
	RAMSAR Convention
	UK Countryside Stewardship Scheme
Water quality regulation	National initiatives: Integrated Mangrove Aquaculture System (China); Great Lakes Restoration Initiative (N. America).
Pest regulation	Agri-environment schemes (UK)
Pollination	Agri-environment schemes
	Conservation areas/ nature reserves
	Conservation of Agricultural Resource Act (California)
	EU organic farming regulation (2092/91/EEC)
	Organic Food Act (California, US)
	UKs 2020 Biodiesel Target (part of policy to reduce GHG and other emissions from transport)
Recreation (species-based)	Action Plan for Biodiversity and Nature Conservation (Denmark)
	Buffer zone regulations (Nepal government, 1996 to establish buffer zones around existing protected areas)
	Endangered Species Act Policies (e.g. for lions)
	Implementation of regulations relating to listed threatened of protected species (TOPS, South Africa)
	Local laws (e.g. ban of catch and release fishing in Germany)
	Natura 2000 Network
	Preventative policy against crocodile attacks (Australia)
	Recreational hunting as a policy for population control of feral pigs (US, California)
	River Catchment Management Plans (e.g. for River Spey)
	Rottnest Island Authority Act (1987, Western Australia, establishes the Rottnest Island Authority as a statutory body to control and manage the Island, reporting to the

Ecosystem Service	Additional policies cited
	Minister for Tourism)
	Tourism Development Strategies
	Tourist hunting regulations (e.g. Tanzania, 2010)
	Use of permits (e.g. to assess risk to bat species from tourism, to reduce impacts of swimming with dolphins, Australia)
Aesthetic landscapes	Act on Urban Parks and Green Spaces (Korea)
	Creation and Management of Forest Resources Act (Korea)
	Establishment and Management of Forest Resource Act (Korea)
	Framework act on forestry (Korea)
	Red grouse hunting policy

Annex 5: Short reports for each ecosystem service

Please note that Annex 5 will be updated in line with the changes made to this second version of the main report. The new version of Annex 5 will be released at a later stage. In the meantime, the previous version of Annex 5 is still present in the first version of this report on the OpenNESS website.

Annex 6: The OpenNESS database tool

A new database tool was developed to store and analyse the material from the OpenNESS literature review. The tool is a Windows application with a local MS Access database that was already filled with details of the earlier BESAFE study, containing 630 papers. Each reviewer filled in their own copy of the database with details from the 60 selected papers for the 13 chosen ecosystem services.

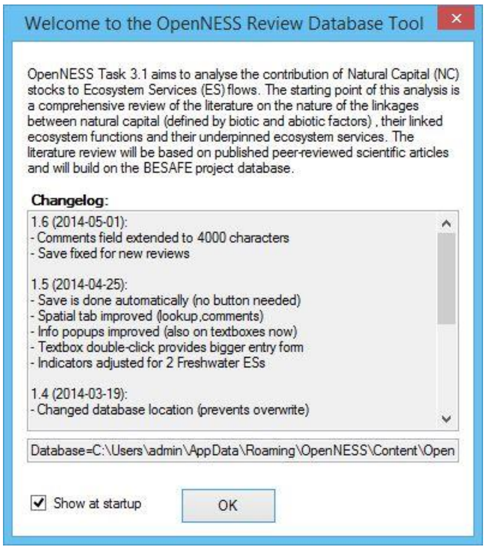
The interface allows users to fill in details of each paper using the following tabs: Reference, Interaction with other ecosystem services, Spatial scale and locations, Temporal scale, Ecosystem types & conditions, Ecosystem Service Provider Classes, Attribute trait classes, Abiotic factors, Human input and management, Indicators, Thresholds, Policies, Evidence, and Comments. Screenshots for each of these tabs are shown below. Most of the entry fields were enhanced with a comment field to gather more information when applicable. Spatial data can be entered using Bing Maps and are stored as a bounding box combined with a scale: Local, (Sub)National, (Sub)Continental, and Global.

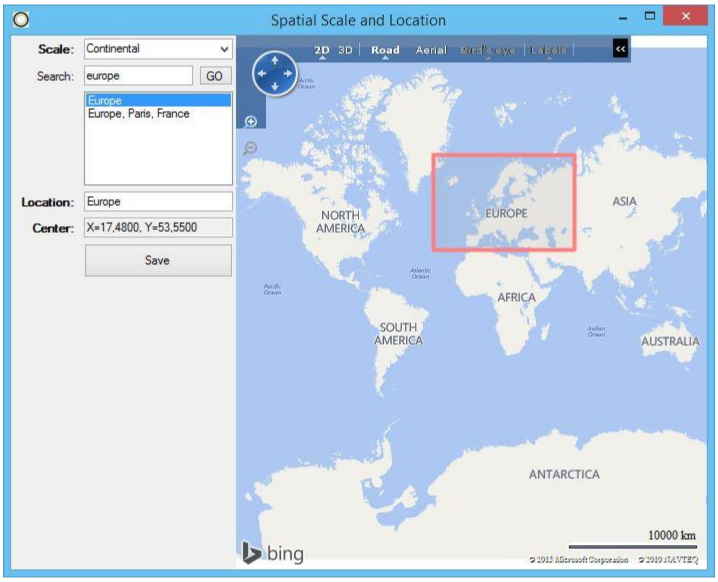
During the reviewing phase all reviewers sent in their database several times for checks and creating summaries for progress purposes. For this, the tool was enhanced to combine all the completed reviews and extract data into Excel sheets, and to generate maps and network diagrams.

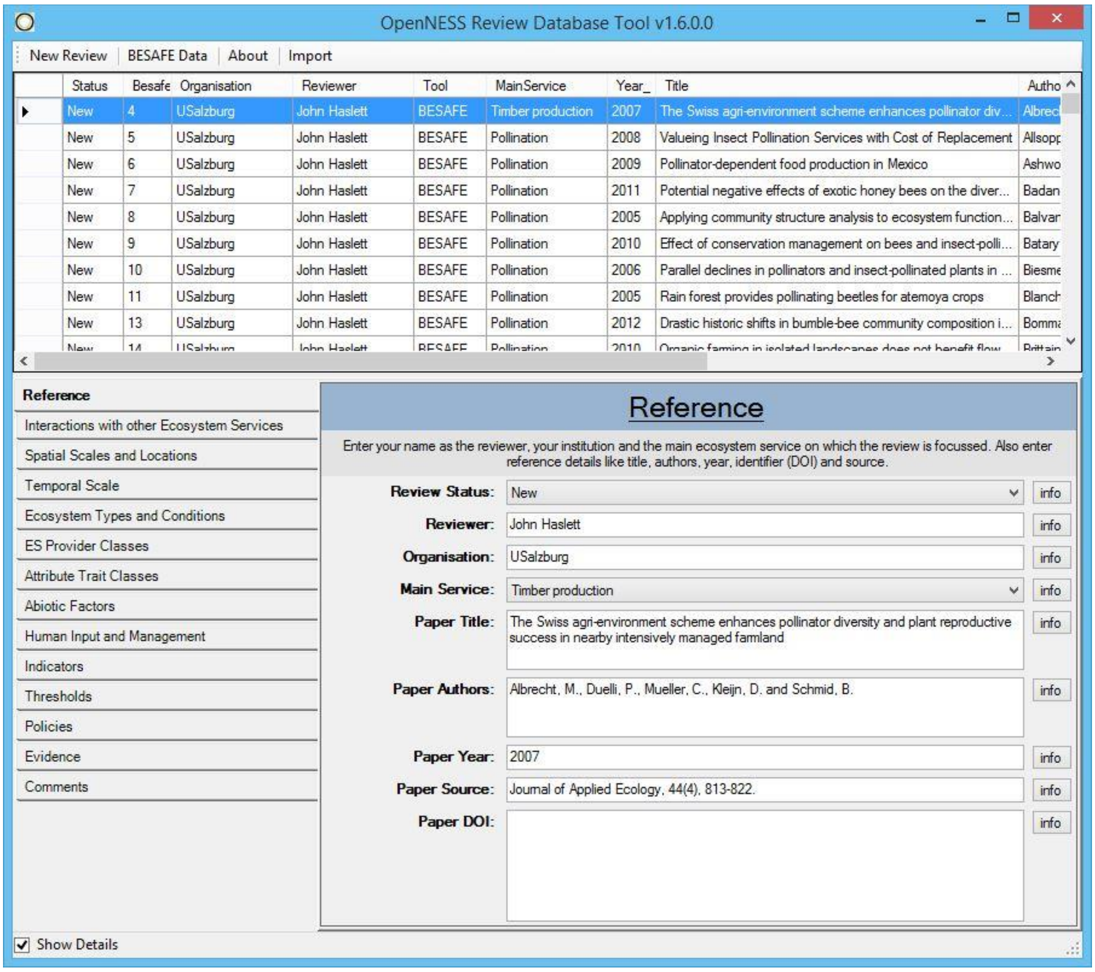
Technical details

The tool is a .NET 3.5 32-bit !WinForms application developed in C# with Visual Studio 2012. The components are NHibernate (OR/M) and !StructureMap (Dependency Injection). The database was generated using NHibernate and filled with lookup values from an Excel-sheet. This mechanism proved to be very flexible during the design phase, as fields and values could be easily changed. The user interface is generated at run-time and each entry field (textbox, checkbox or dropdown) is linked to a field in the database. Maps are generated using Google Maps and an overlay of spatial locations. Network diagrams showing the interactions between ecosystem services are created with a custom version of the Diagram.NET library.

Screenshots


Welcome to the OpenNESS Review Database Tool
OpenNESS Task 3.1 aims to analyse the contribution of Natural Capital (NC) stocks to Ecosystem Services (ES) flows. The starting point of this analysis is a comprehensive review of the literature on the nature of the linkages between natural capital (defined by biotic and abiotic factors) , their linked ecosystem functions and their underpinned ecosystem services. The literature review will be based on published peer-reviewed scientific articles and will build on the BESAFE project database.
Changelog:
1.6 (2014-05-01):
- Comments field extended to 4000 characters
- Save fixed for new reviews
1.5 (2014-04-25):
- Save is done automatically (no button needed)
- Spatial tab improved (lookup,comments)
- Info popups improved (also on textboxes now)
- Textbox double-click provides bigger entry form
- Indicators adjusted for 2 Freshwater ESs
1.4 (2014-03-19):
- Changed database location (prevents overwrite)
Database=C:\Users\admin\AppData\Roaming\OpenNESS\Content\Open
Show at startup
OK


Spatial Scale and Location
Scale: Continental
Search: europe
GO
Europe
Europe, Paris, France
Location: Europe
Center: X=17.4800, Y=53.5500
Save
2D 3D Road Aerial
NORTH AMERICA
EUROPE
ASIA
AFRICA
SOUTH AMERICA
AUSTRALIA
ANTARCTICA
10000 km
bing


OpenNESS Review Database Tool v1.6.0.0
New Review
BESAFE Data
About
Import
Status | Besafe | Organisation | Reviewer | Tool | MainService | Year_ | Title | Autho
New | 4 | USalzburg | John Haslett | BESAFE | Timber production | 2007 | The Swiss agri-environment scheme enhances pollinator div... | Albrec
New | 5 | USalzburg | John Haslett | BESAFE | Pollination | 2008 | Valueing Insect Pollination Services with Cost of Replacement | Allsopp
New | 6 | USalzburg | John Haslett | BESAFE | Pollination | 2009 | Pollinator-dependent food production in Mexico | Ashwo
New | 7 | USalzburg | John Haslett | BESAFE | Pollination | 2011 | Potential negative effects of exotic honey bees on the diver... | Badan
New | 8 | USalzburg | John Haslett | BESAFE | Pollination | 2005 | Applying community structure analysis to ecosystem function... | Balvar
New | 9 | USalzburg | John Haslett | BESAFE | Pollination | 2010 | Effect of conservation management on bees and insect-polli... | Batary
New | 10 | USalzburg | John Haslett | BESAFE | Pollination | 2006 | Parallel declines in pollinators and insect-pollinated plants in ... | Biesme
New | 11 | USalzburg | John Haslett | BESAFE | Pollination | 2005 | Rain forest provides pollinating beetles for atemoya crops | Blanch
New | 13 | USalzburg | John Haslett | BESAFE | Pollination | 2012 | Drastic historic shifts in bumble-bee community composition i... | Bomm
Reference
Interactions with other Ecosystem Services
Spatial Scales and Locations
Temporal Scale
Ecosystem Types and Conditions
ES Provider Classes
Attribute Trait Classes
Abiotic Factors
Human Input and Management
Indicators
Thresholds
Policies
Evidence
Comments
Reference
Enter your name as the reviewer, your institution and the main ecosystem service on which the review is focussed. Also enter reference details like title, authors, year, identifier (DOI) and source.
Review Status: New
Reviewer: John Haslett
Organisation: USalzburg
Main Service: Timber production
Paper Title: The Swiss agri-environment scheme enhances pollinator diversity and plant reproductive success in nearby intensively managed farmland
Paper Authors: Albrecht, M., Duelli, P., Mueller, C., Kleijn, D. and Schmid, B.
Paper Year: 2007
Paper Source: Journal of Applied Ecology, 44(4), 813-822.
Paper DOI:
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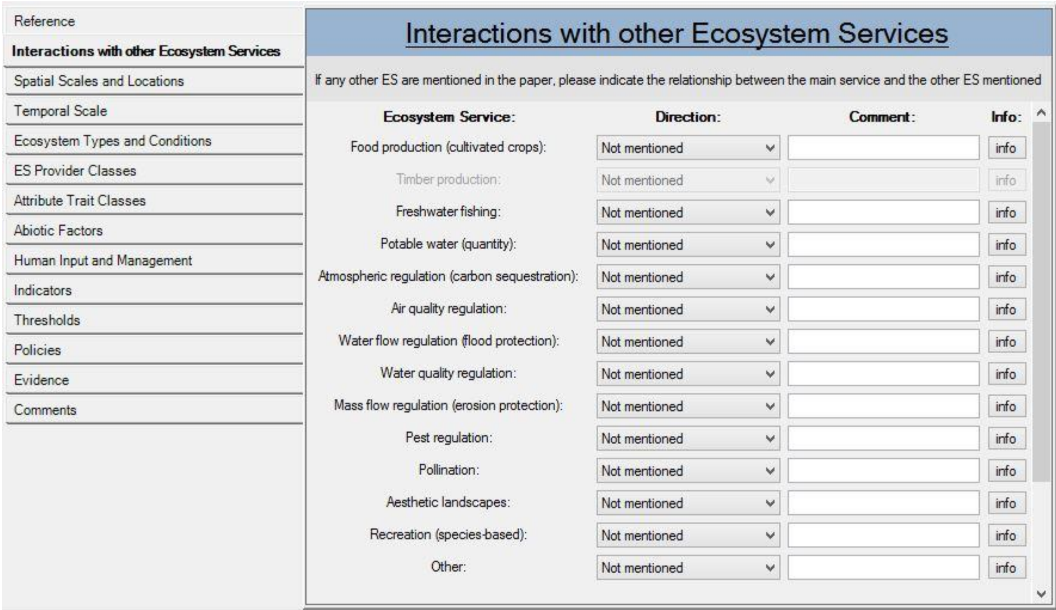
Show Details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ES Provider Classes
Attribute Trait Classes
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Interactions with other Ecosystem Services
If any other ES are mentioned in the paper, please indicate the relationship between the main service and the other ES mentioned
Ecosystem Service:
Direction:
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Info:
Food production (cultivated crops):
Timber production:
Freshwater fishing:
Potable water (quantity):
Atmospheric regulation (carbon sequestration):
Air quality regulation:
Water flow regulation (flood protection):
Water quality regulation:
Mass flow regulation (erosion protection):
Pest regulation:
Pollination:
Aesthetic landscapes:
Recreation (species-based):
Other:
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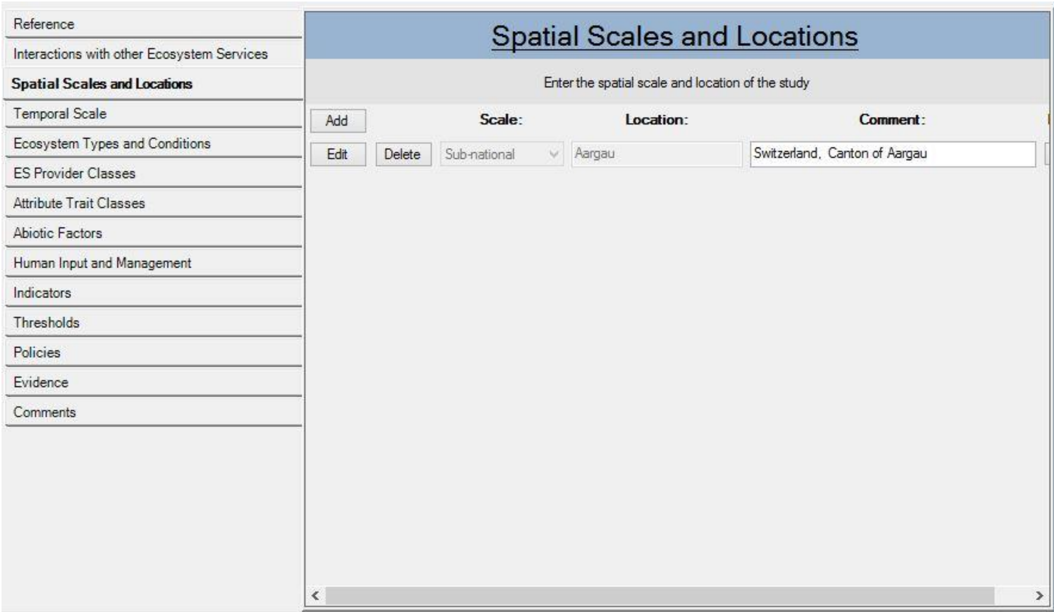
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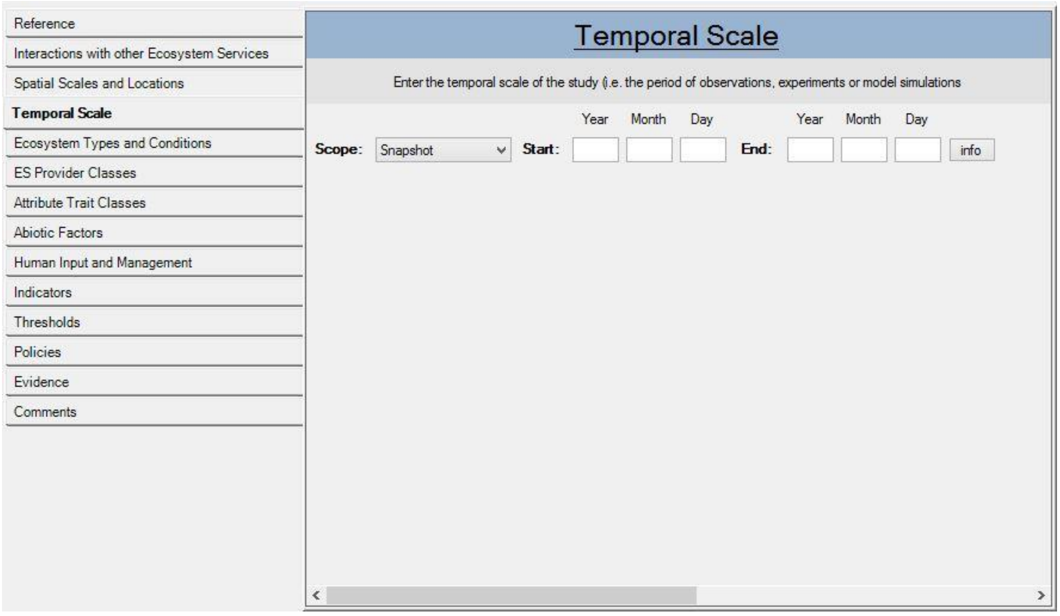
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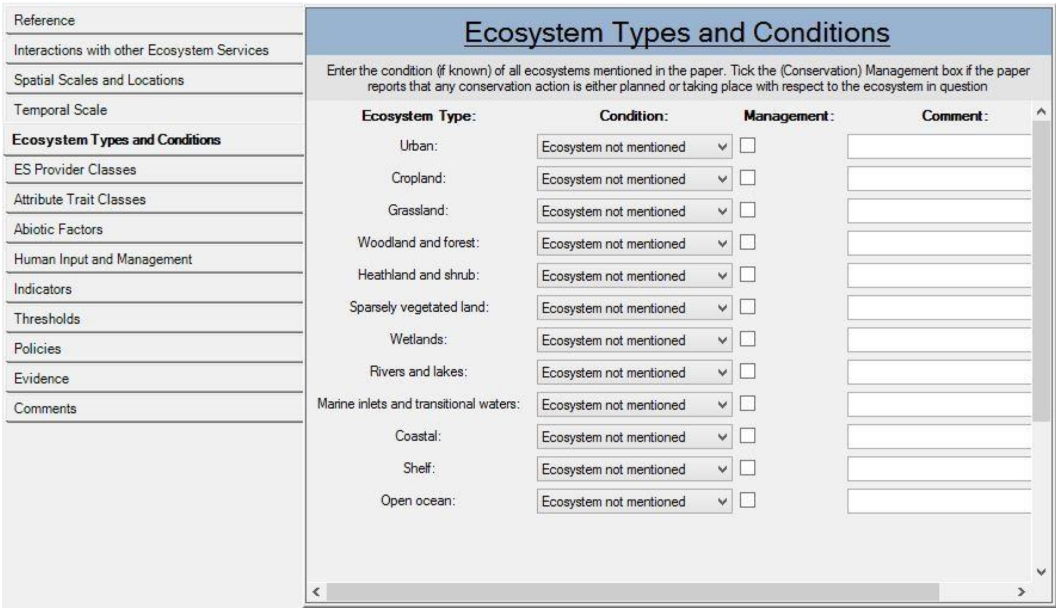
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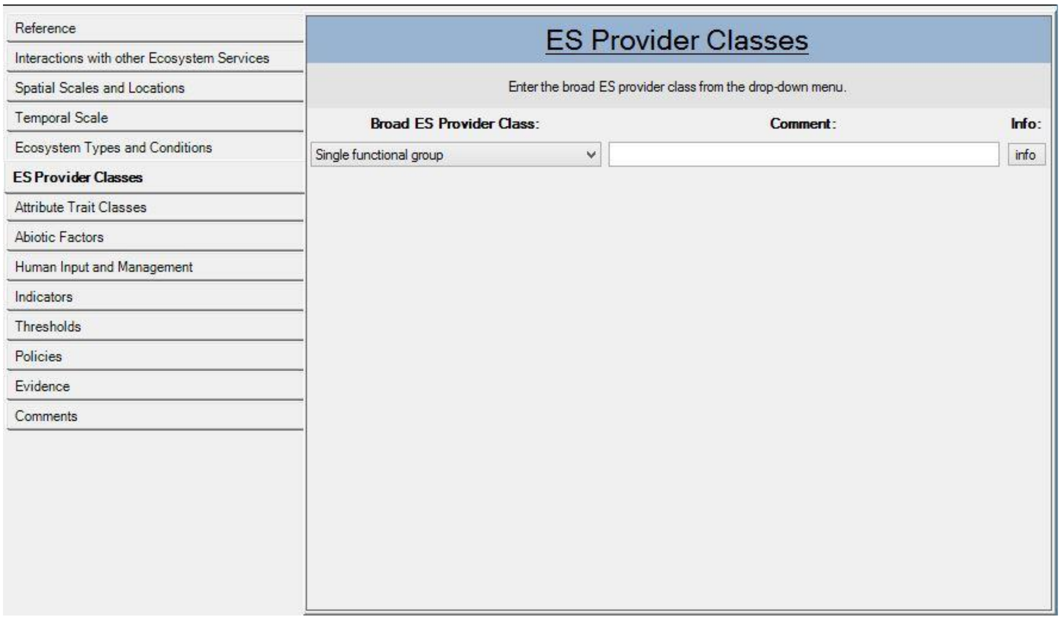
Ecosystem Types and Conditions
Enter the condition (if known) of all ecosystems mentioned in the paper. Tick the (Conservation) Management box if the paper reports that any conservation action is either planned or taking place with respect to the ecosystem in question
Ecosystem Type: Condition: Management: Comment:
Urban: Ecosystem not mentioned
Cropland: Ecosystem not mentioned
Grassland: Ecosystem not mentioned
Woodland and forest: Ecosystem not mentioned
Heathland and shrub: Ecosystem not mentioned
Sparsely vegetated land: Ecosystem not mentioned
Wetlands: Ecosystem not mentioned
Rivers and lakes: Ecosystem not mentioned
Marine inlets and transitional waters: Ecosystem not mentioned
Coastal: Ecosystem not mentioned
Shelf: Ecosystem not mentioned
Open ocean: Ecosystem not mentioned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ES Provider Classes
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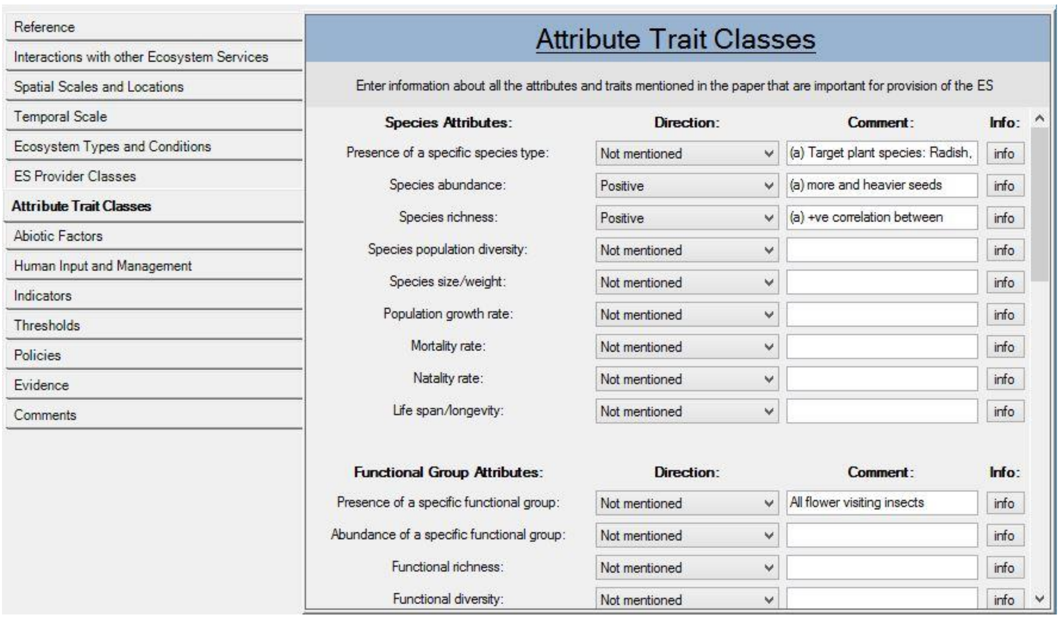
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Attribute Trait Classes
Enter information about all the attributes and traits mentioned in the paper that are important for provision of the ES
Species Attributes:
Direction:
Comment:
Info:
Presence of a specific species type:
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(a) Target plant species: Radish,
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Species abundance:
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(a) more and heavier seeds
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Species richness:
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(a) +ve correlation between
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Species population diversity:
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Species size/weight:
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Population growth rate:
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Mortality rate:
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Natality rate:
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Life span/longevity:
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Functional diversity:
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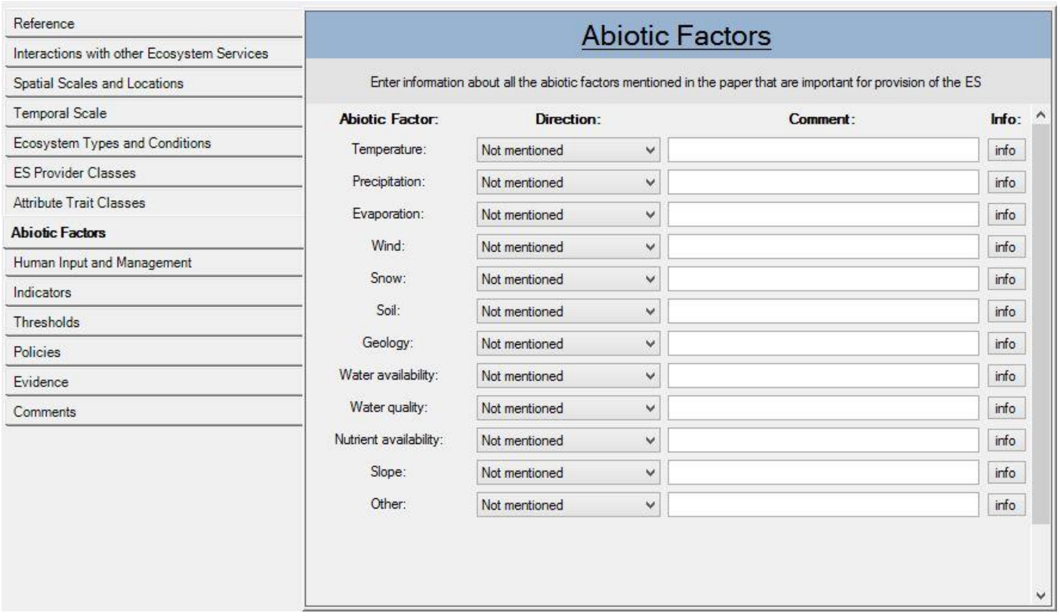
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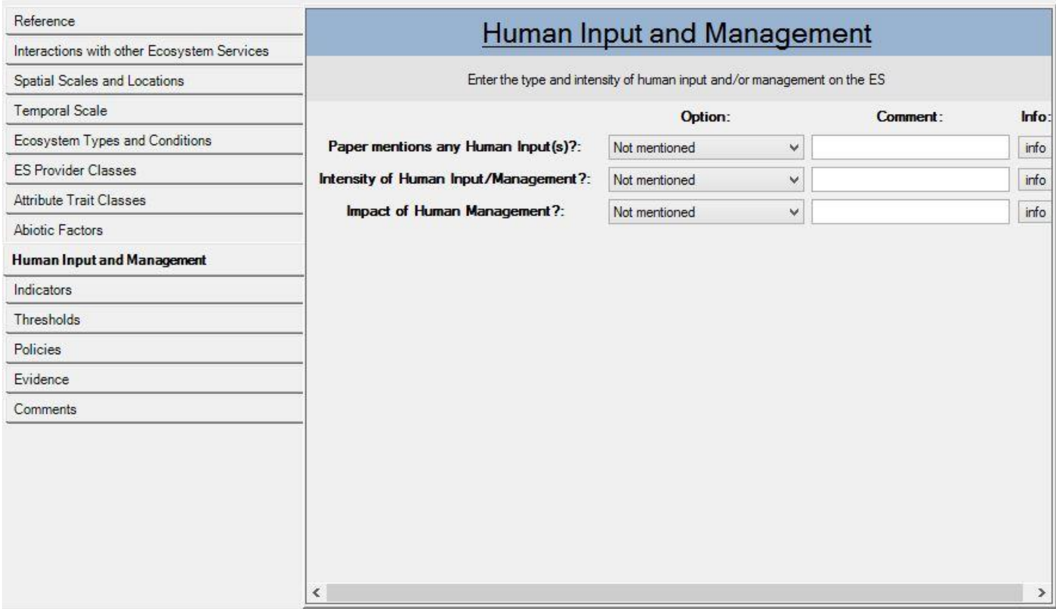
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Human Input and Management
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Impact of Human Management?:
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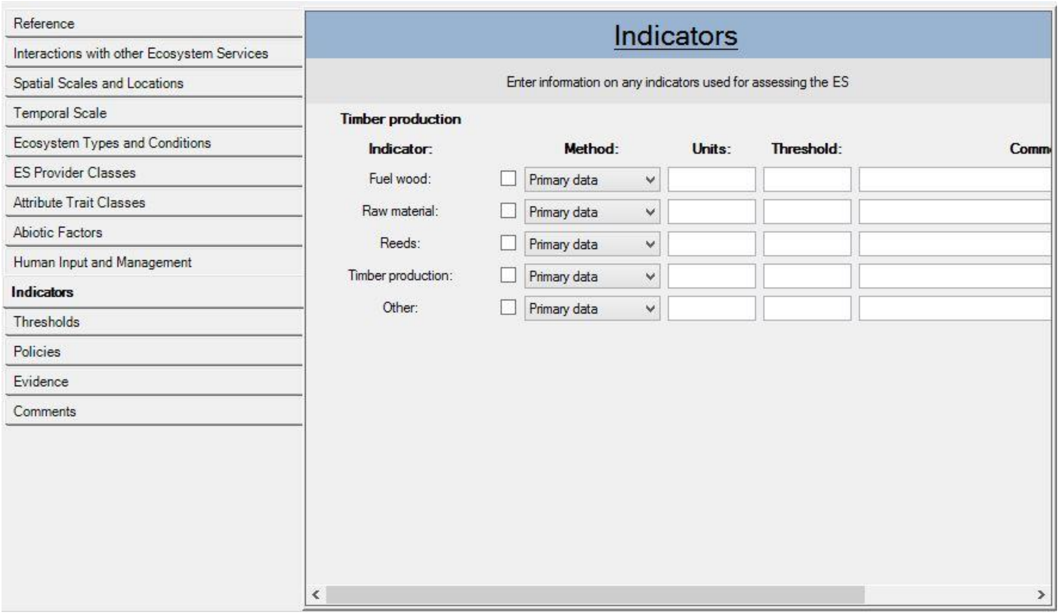
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Indicators
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Timber production
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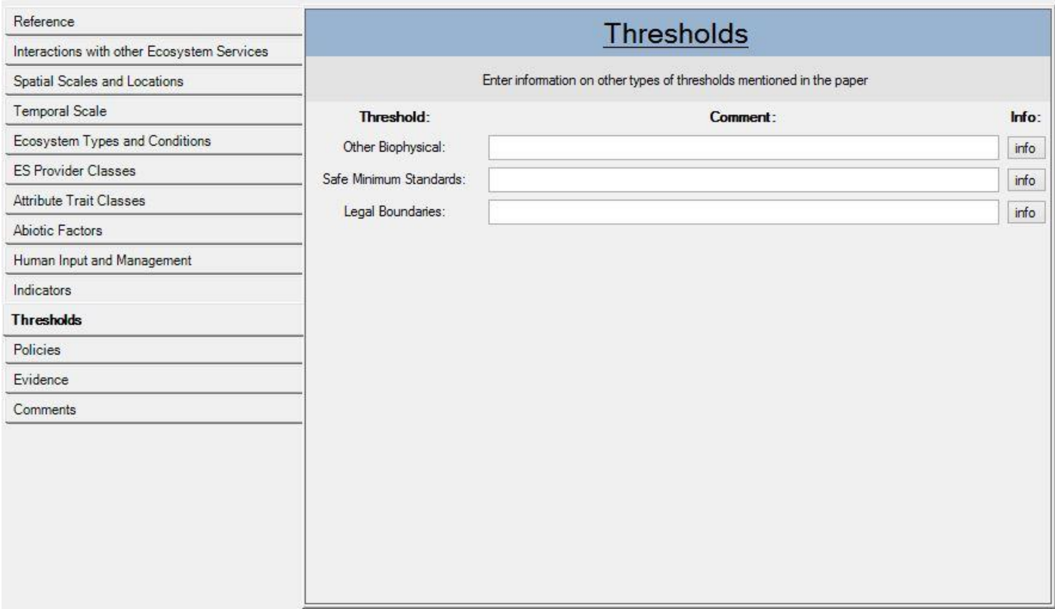
Raw material:
Primary data
Reeds:
Primary data
Timber production:
Primary data
Other:
Primary data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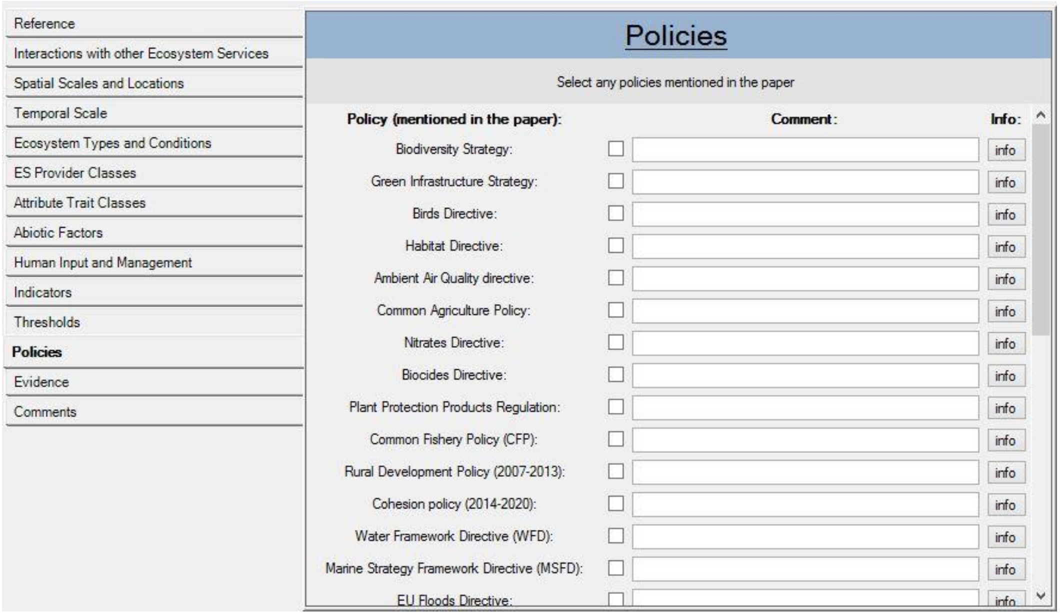
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Policies
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Policy (mentioned in the paper):
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Biodiversity Strategy:
Green Infrastructure Strategy:
Birds Directive:
Habitat Directive:
Ambient Air Quality directive:
Common Agriculture Policy:
Nitrates Directive:
Biocides Directive:
Plant Protection Products Regulation:
Common Fishery Policy (CFP):
Rural Development Policy (2007-2013):
Cohesion policy (2014-2020):
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Marine Strategy Framework Directive (MSFD):
EU Floods Directive:
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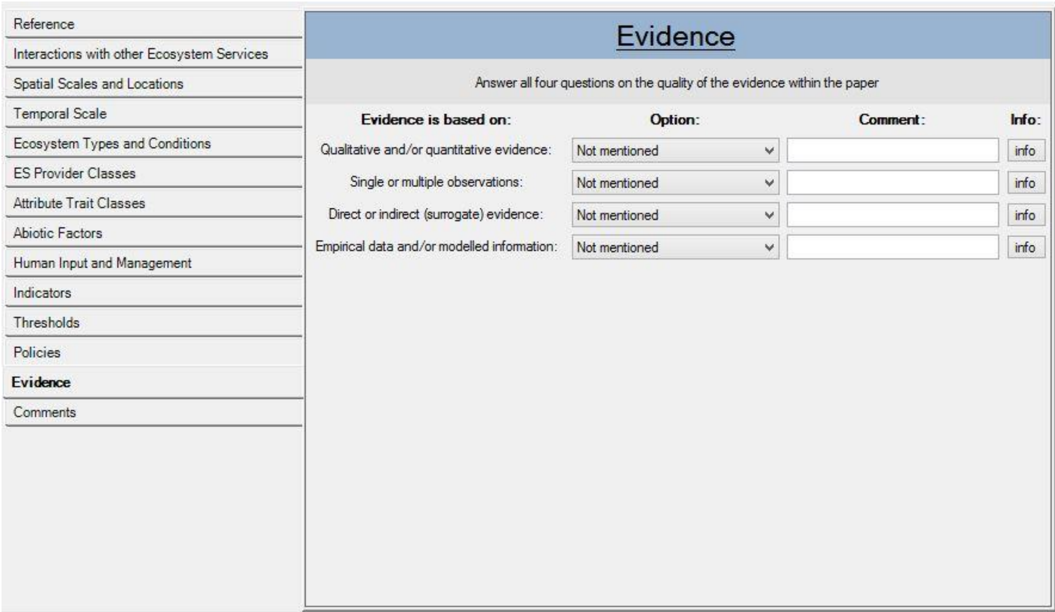
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Evidence
Answer all four questions on the quality of the evidence within the paper
Evidence is based on:
Option:
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Qualitative and/or quantitative evidence:
Single or multiple observations:
Direct or indirect (surrogate) evidence:
Empirical data and/or modelled information:
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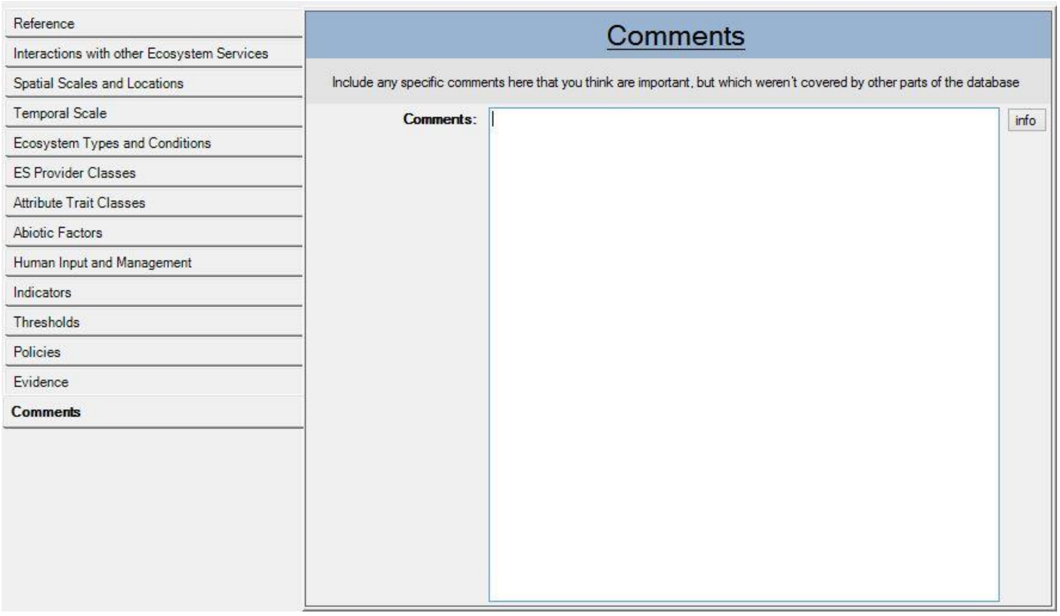
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Include any specific comments here that you think are important, but which weren't covered by other parts of the database
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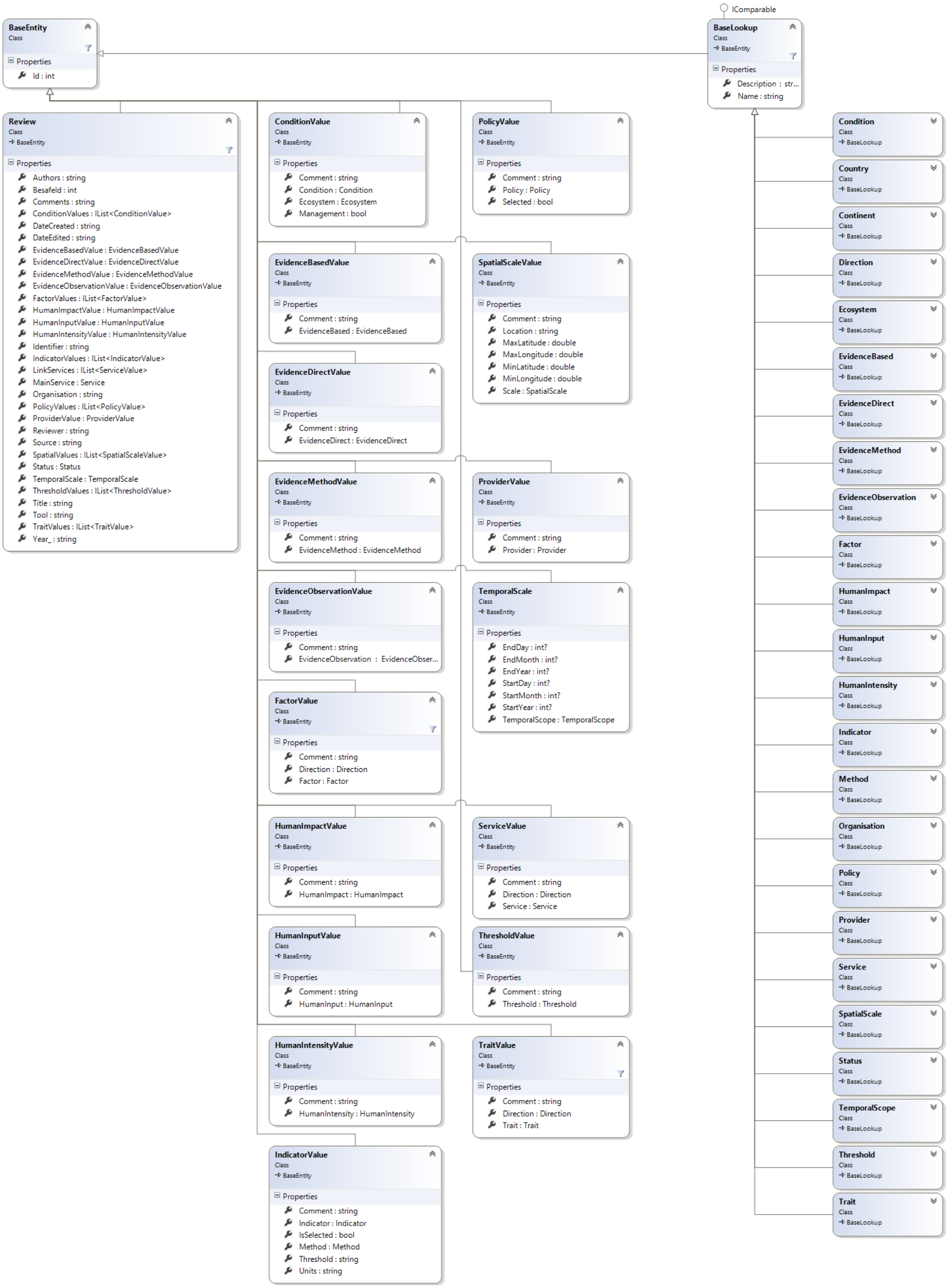
Domain Model



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