

How natural capital delivers ecosystem services: a typology derived from a systematic review. Supplementary Material

1 Overview across all ecosystem services

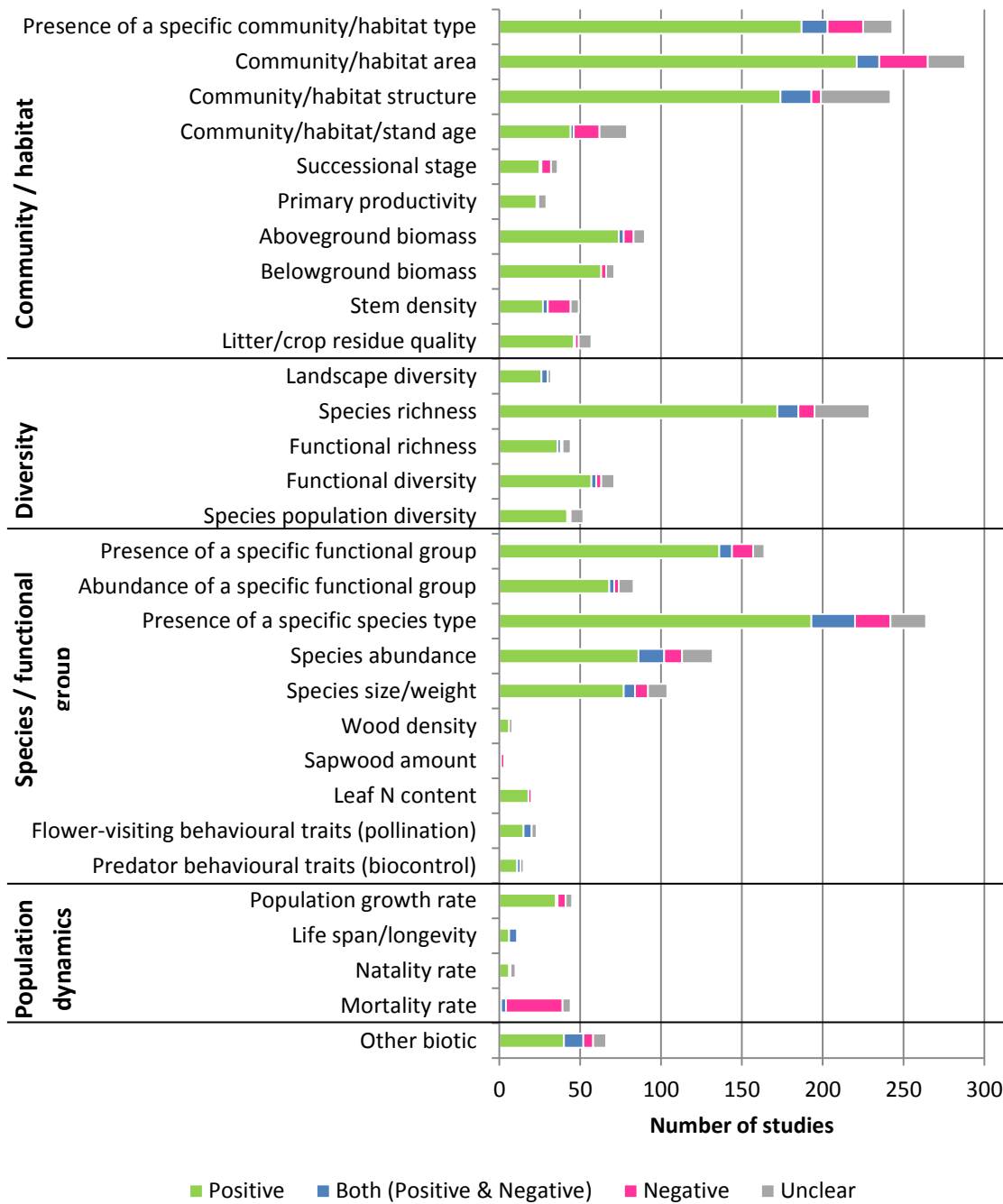


Figure S1: Number of studies reviewed that cite links between biotic attributes and ecosystem service delivery. A total of 780 studies were reviewed. The colours of the bar segments indicate the direction of influence of the biotic attribute on the ecosystem service. “Both” indicates cases where an attribute had both a positive and negative influence on the service. “Unclear” indicates cases where the direction of the link was uncertain.

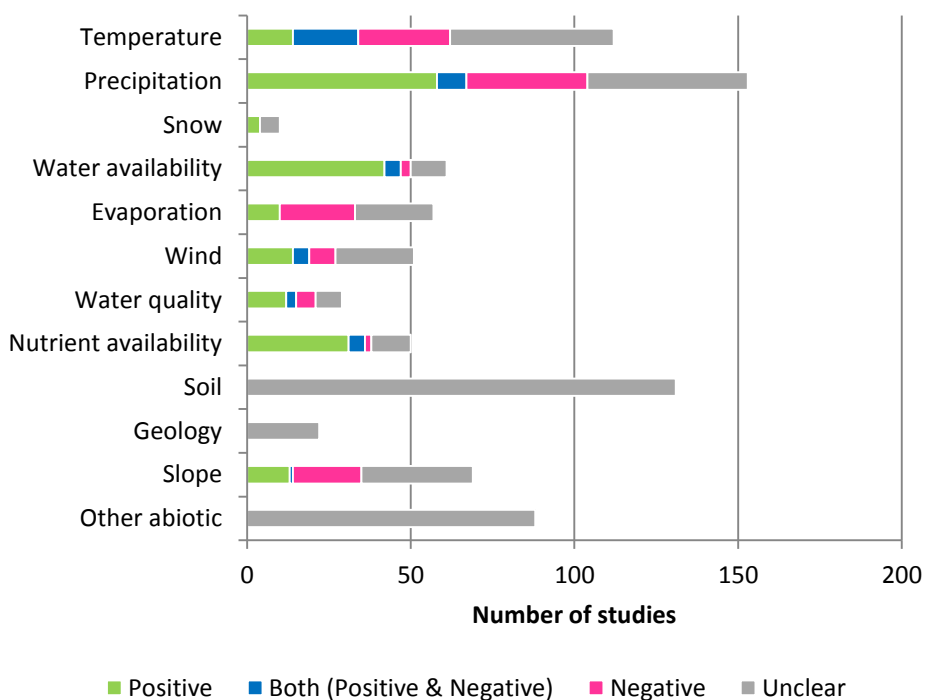


Figure S2: Number of articles reviewed that cite links between abiotic factors and ecosystem service delivery. A total of 780 studies were reviewed. The colours of the bar segments indicate the direction of influence of the abiotic factor on the ecosystem service. “Both” indicates cases where an attribute had both a positive and negative influence on the service. “Unclear” indicates cases where the direction of the link was uncertain.

2 Network diagrams for ecosystem services

References for this section are in Appendix D.

2.1 Regulating services

2.1.1 Atmospheric regulation (carbon storage)

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. 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.

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. For example, Tran van Con et al. (2013) find that the link between diversity and carbon storage is highest within a particular site, and may not be evident in broader scale comparisons due to differences in other environmental factors. They suggest that resource-use complementarity is most evident in structurally complex forests with multiple canopy layers, and that diversity may have a lower impact in simpler forests with few species. Site productivity may also be important: Potter and Woodall (2014) find that although higher carbon storage can be achieved by a monoculture of large trees in fertile sites, resource-use complementarity is important for boosting productivity in less fertile sites or those which are challenged by adverse environmental conditions such as droughts. Successional stage may be a confounding factor, as more mature (and therefore more diverse) natural forests have older and larger trees (Gonzalez et al., 2014).

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 (Klump 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).

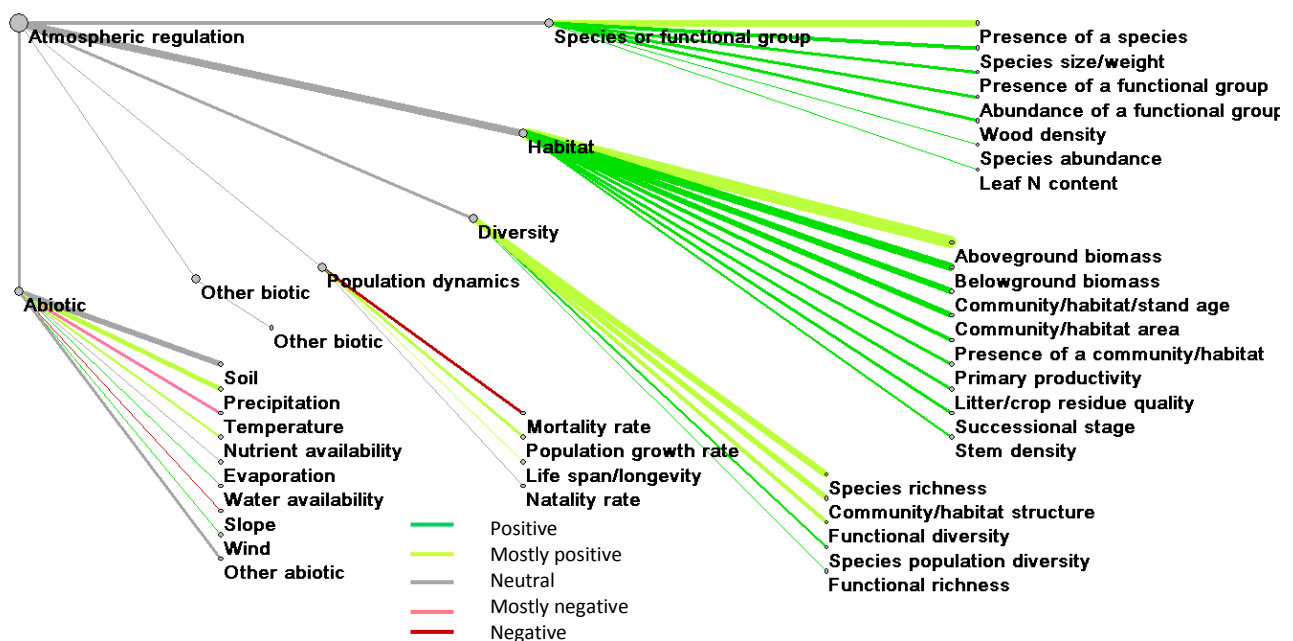


Figure S3. Network diagram mapping the evidence on how biotic attributes and abiotic factors influence the service of atmospheric regulation. Line thickness is proportional to number of studies supporting each link and line colour indicates predominant direction of link.

2.1.2 Air quality regulation

For air quality regulation, there is a split between attributes related to the entire habitat (typically urban woodland), and particular species or functional groups such as 'urban trees' or 'coniferous trees' (Figure S6). Community/habitat area (i.e. the percentage of tree cover) is a key attribute, and so is the leaf area index (i.e. the ratio between leaf surface area and ground area), which was not included in the original list of attributes and so is recorded under 'other biotic'. However, many of the studies compare different tree

species, trying to find those most suitable for planting in urban areas in order to improve air quality. Species characteristics such as leaf size, shape (needle or broad-leaved), stickiness and hairiness are often investigated. Most articles conclude that coniferous trees are more effective at trapping pollution because their needle-shaped leaves have a high surface area, and because they are mainly evergreens and therefore can contribute to air quality all year round (e.g. Tallis et al., 2011). However, they may not be tolerant of high roadside pollution levels and salt from road run-off, so might not be appropriate for the ‘front-line’ positions immediately next to busy roads (Saebo et al., 2012).

The impacts of the abiotic factors are complex and context-dependent. Wind can have a beneficial effect locally by dispersing pollution away from city streets or increasing deposition rates on leaves, but it can also re-suspend deposited particles (Nowak et al., 2006). High temperatures can decrease uptake of pollutants by plants (Alonso et al., 2011) and may also have a negative impact because certain tree species emit biogenic volatile organic compounds (B-VOCs) such as isoprene in hot weather, and these react with nitrogen oxides from traffic to form ground-level ozone pollution (Salmond et al., 2013). However, there can also be a beneficial effect in the range where warmer temperatures enhance plant growth, thus increasing the amount of vegetation that can trap pollutants.

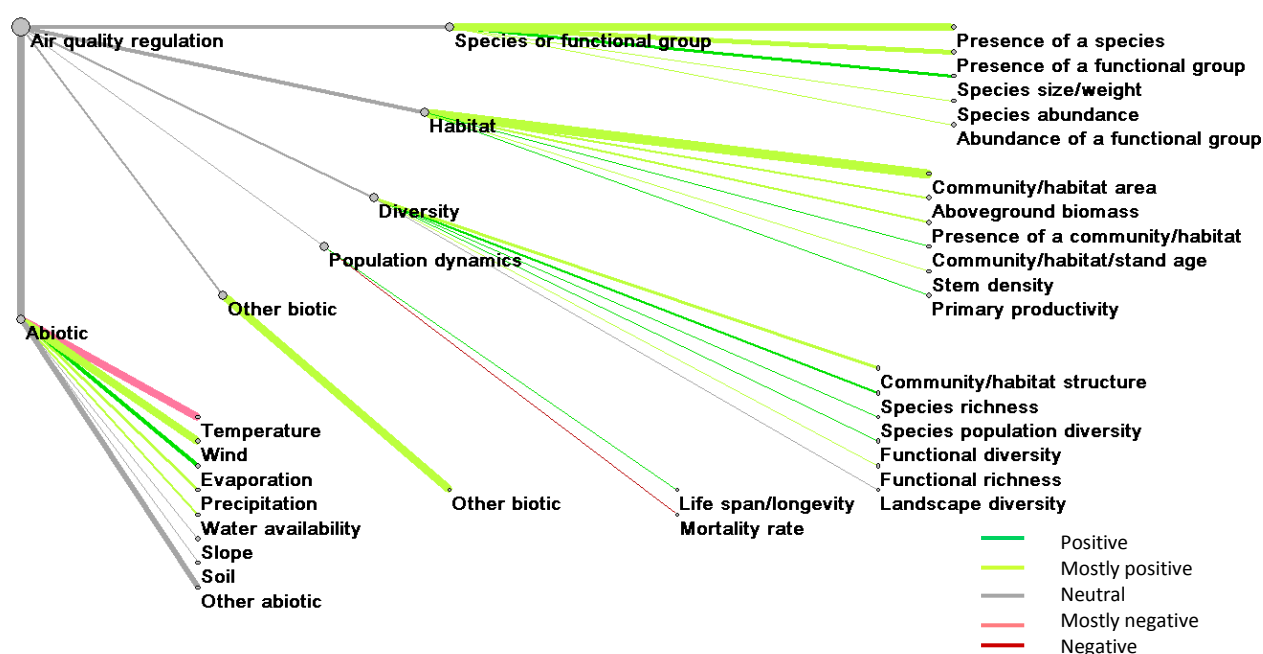


Figure S4. Network diagram mapping the evidence on how biotic attributes and abiotic factors influence the service of air quality regulation. Line thickness is proportional to number of studies supporting each link and line colour indicates predominant direction of link.

2.1.3 Water flow regulation (flood protection)

Most of the articles reviewed for this service describe ‘paired catchment’ studies which compare two similar catchments with different forest cover, or the same catchment before and after felling. Forests reduce peak run-off, by intercepting precipitation, absorbing groundwater through transpiration and improving the infiltration capacity of the soil, so storm flows in streams and rivers increase when catchments are deforested. Community/habitat area is the most commonly identified biotic attribute, as shown by the thickness of the line, and it has a predominantly positive influence on water flow regulation as shown by the light green colour. Several papers cite a threshold effect where storm flows increase noticeably when forest cover in the catchment falls below 20-30% (Bathurst et al., 2010; Lin & Wei, 2008; Schnorbus & Alila, 2013). As larger trees tend to intercept and absorb more water, stand age is 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.

Some articles focus on particular species: these are mainly studies of plantations dominated by single species such as pine or beech. Characteristics of particular species or functional groups are mentioned in some studies, but the results vary depending on the context. For example, Lange et al. (2013) find that the high root density and transpiration rates in beech forest provide greater infiltration and better flood protection than spruce forest, but Hümann et al. (2011) find that conifer forests (spruce and fir) have deeper root systems and lower runoff coefficients than deciduous forests. Both studies therefore agree on the importance of a particular functional group — species with a dense, deep root system — but in one case this function is greater in the deciduous forest and in the other it is greater in the coniferous forest. In three studies, 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, water flow regulation is the only service for which no attributes connected to species/functional richness or diversity are mentioned in the literature. However, structural complexity ('roughness') is found to increase protection against storm surges in coastal vegetation (Mazda et al., 1997; Ferrario et al., 2014) and to increase floodwater retention in floodplain woodlands (Thomas and Nisbet, 2006).

For the abiotic factors, precipitation has a direct negative impact, but there is an interesting debate over the impact of rainfall intensity on the ability of the ecosystem to provide flood protection. The established view is that forest cover has a limited effect for more extreme rainfall events (e.g. Bathurst et al., 2007; Bruijnzeel, 2004; Cheng et al., 2002; Clark, 1987; Moore and Wondzell, 2005). However, Green and Alila (2012) argue that forest cover will always decrease both the frequency and the magnitude of flood events.

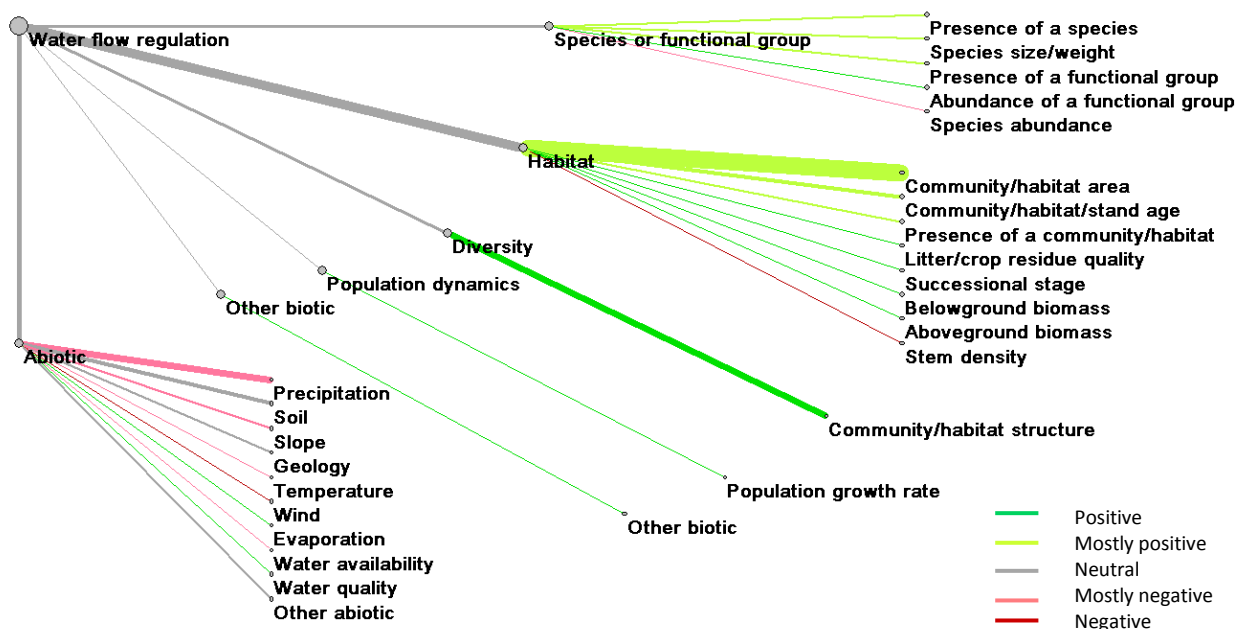


Figure S5. Network diagram mapping the evidence on how biotic attributes and abiotic factors influence the service of water flow regulation (flood protection). Line thickness is proportional to number of studies supporting each link and line colour indicates predominant direction of link.

2.1.4 Mass flow regulation (erosion protection)

For mass flow regulation habitat area is frequently cited, with the area covered by vegetation being crucial, but so are species characteristics. Many studies compare different species of tree, shrub or herbaceous plants to determine which perform best for stabilising eroded slopes. Characteristics such as root depth, strength, density and structure are often found to be important for binding soil particles together and increasing soil infiltration (e.g. de Baets et al., 2009; Pohl et al., 2012). These are classified in the review as below-ground biomass or presence/abundance of a functional group such as ‘deep-rooted shrubs’. However, the structure, strength and elasticity of the above-ground vegetation is also cited as being important for intercepting rainfall, resisting water flow and trapping sediment, and the thickness and quality of the litter layer plays a key role in improving soil structure and protecting the soil surface from erosion (e.g. Andry et al., 2007).

For mass flow regulation, forests are not always the best-performing habitat: sometimes fast-growing herbaceous vegetation or permanent grassland can provide better ground cover in the short term, compared to a newly planted forest where the gaps between the trees are bare (Huang et al., 2006). Also, taller trees are not always best as they can exert more pressure on slopes (e.g. Bochet et al., 2006). Species richness and diversity is found to be beneficial by increasing the total vegetation cover and the range of root depths in the soil (e.g. Wang et al., 2012).

With regard to the abiotic factors, precipitation clearly has an adverse impact as most erosion occurs during extreme rainfall events. Steep slopes also exacerbate soil erosion. However, water availability has a beneficial impact as water is necessary for vegetation to become established, thus stabilising and protecting the slope. Drought conditions therefore often lead to more intense soil erosion.

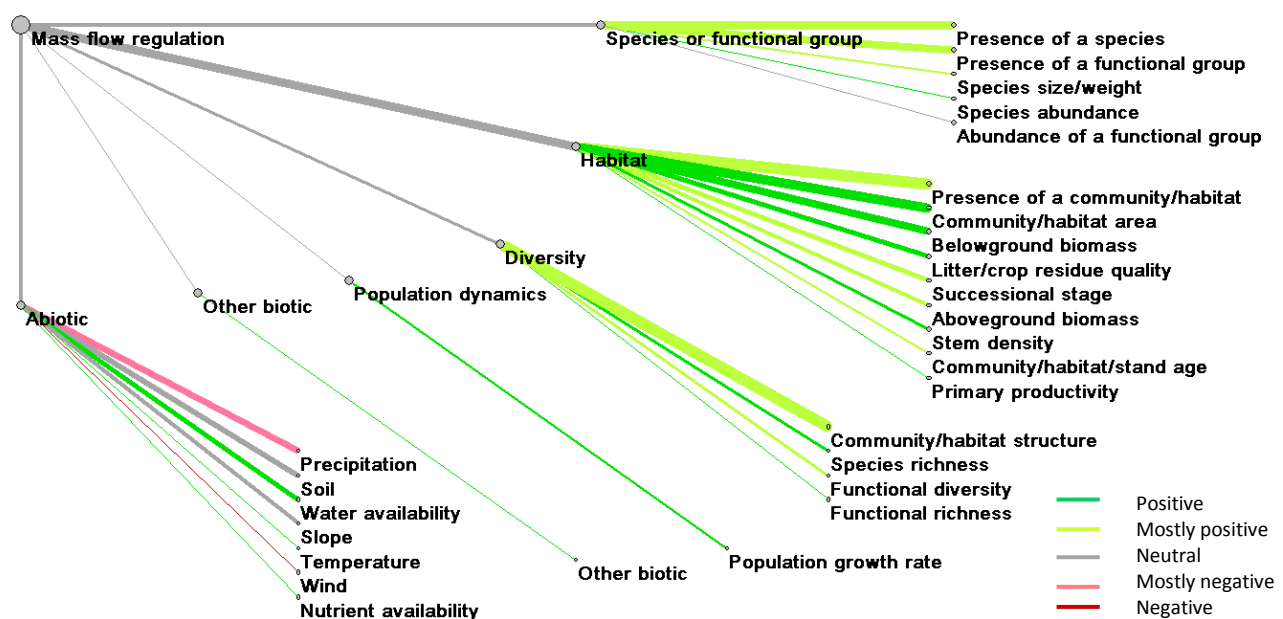


Figure S6. Network diagram mapping the evidence on how biotic attributes and abiotic factors influence the service of mass flow regulation (erosion protection). Line thickness is proportional to number of studies supporting each link and line colour indicates predominant direction of link.

2.1.5 Water quality regulation

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. 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.

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.

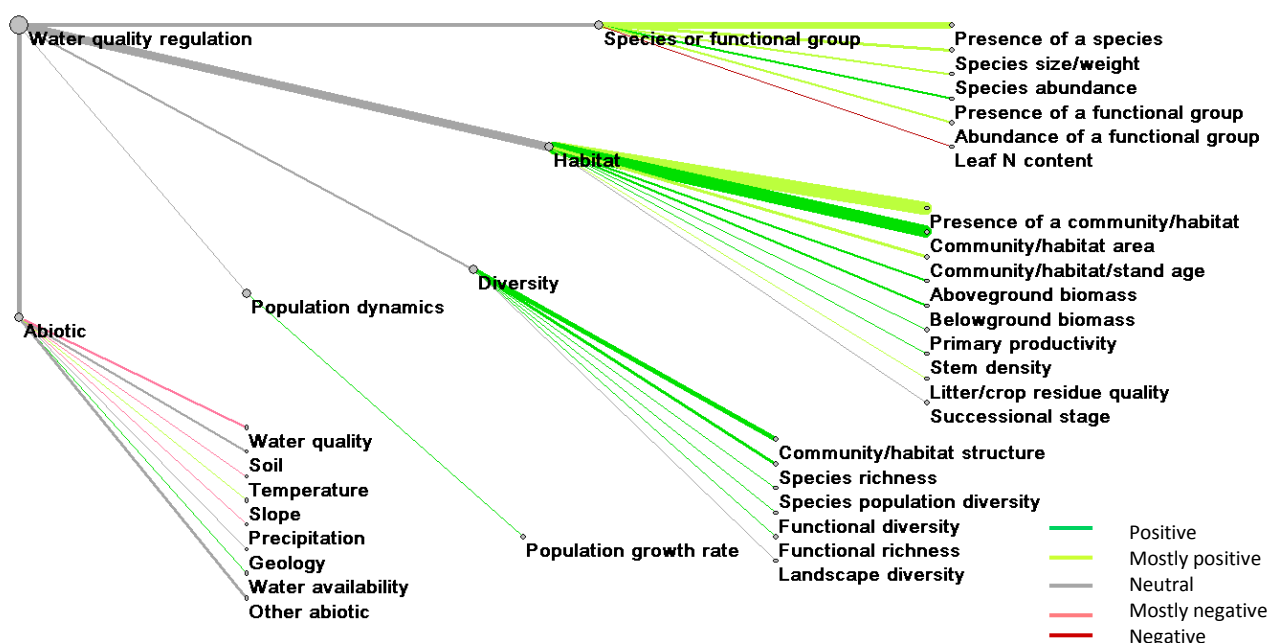


Figure S7. Network diagram mapping the evidence on how biotic attributes and abiotic factors influence the service of water quality regulation. Line thickness is proportional to number of studies supporting each link and line colour indicates predominant direction of link.

2.1.6 Pollination

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).

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.

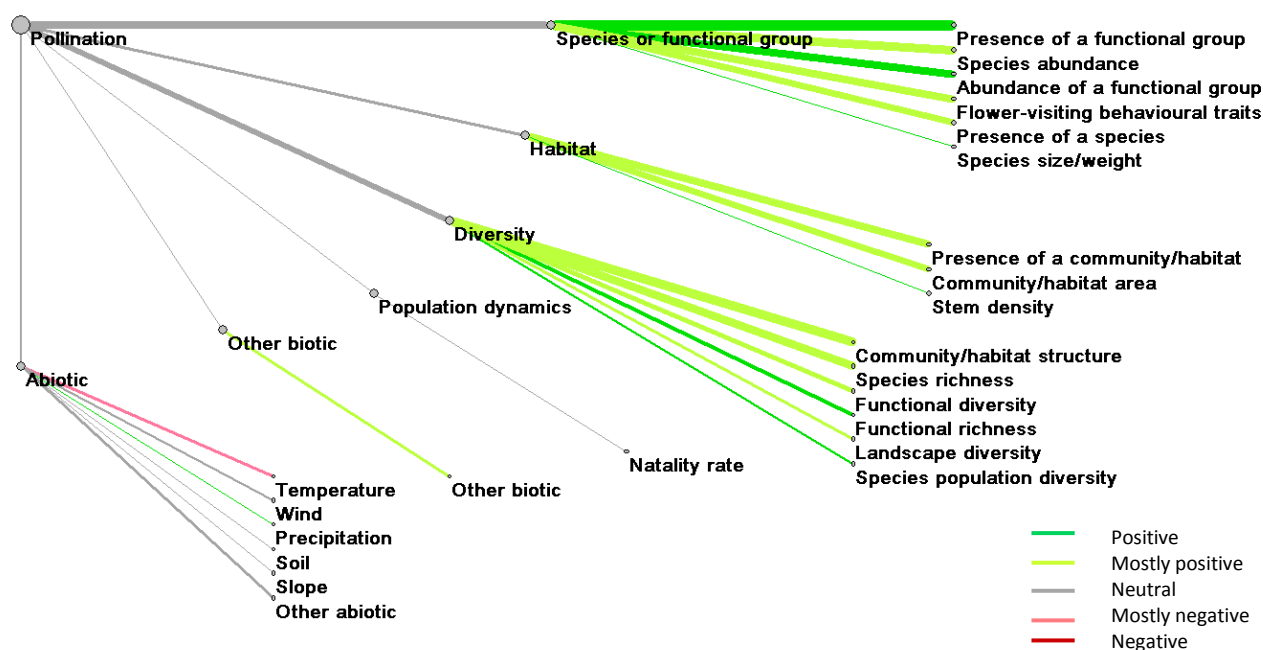


Figure S8. Network diagram mapping the evidence on how biotic attributes and abiotic factors influence the service of pollination. Line thickness is proportional to number of studies supporting each link and line colour indicates predominant direction of link.

2.1.7 Pest regulation

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 (Ipert, 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.

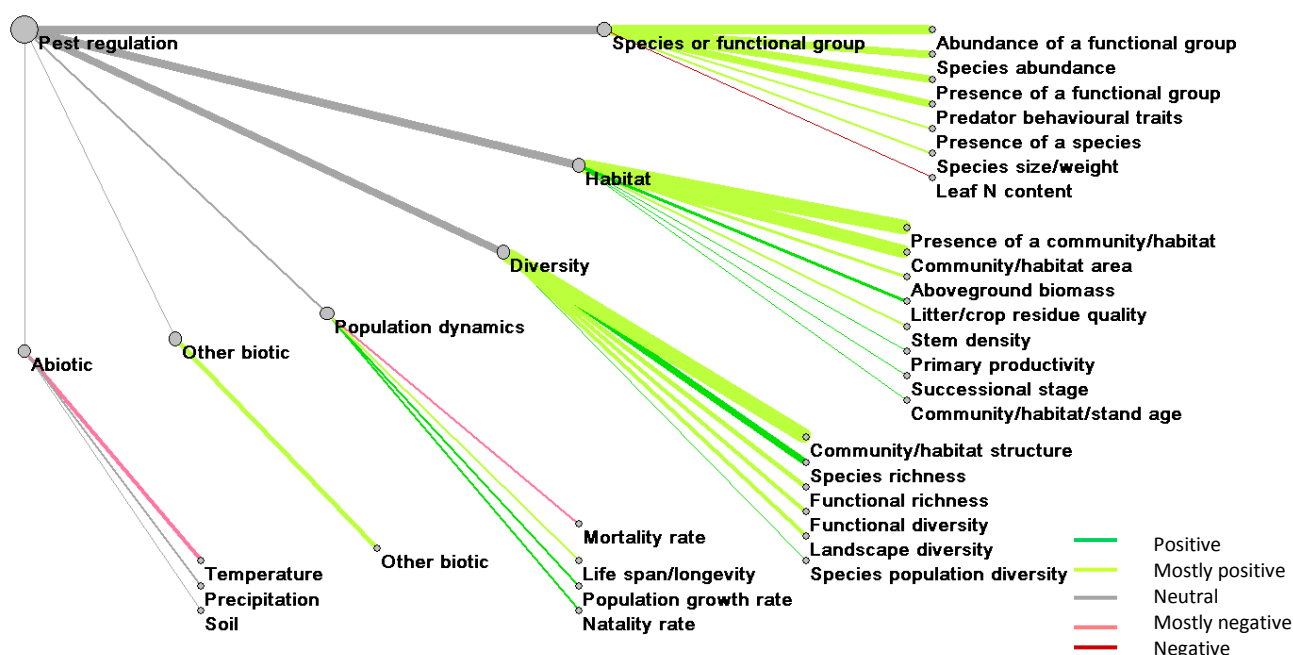


Figure S9. Network diagram mapping the evidence on how biotic attributes and abiotic factors influence the service of pest regulation. Line thickness is proportional to number of studies supporting each link and line colour indicates predominant direction of link.

2.2 Provisioning services

2.2.1 Freshwater fishing

Species-level attributes are the most frequently discussed, 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.

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.

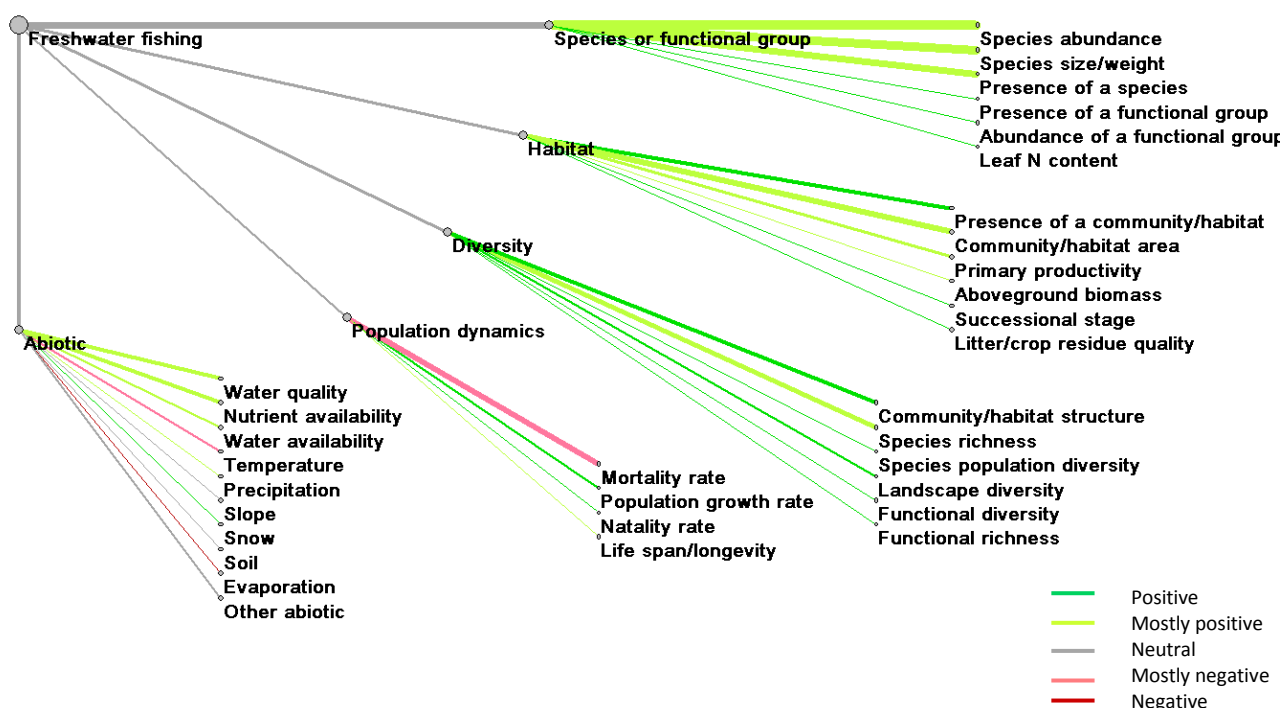


Figure S10. Network diagram mapping the evidence on how biotic attributes and abiotic factors influence the service of freshwater fishing. Line thickness is proportional to number of studies supporting each link and line colour indicates predominant direction of link.

2.2.2 Timber production

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.

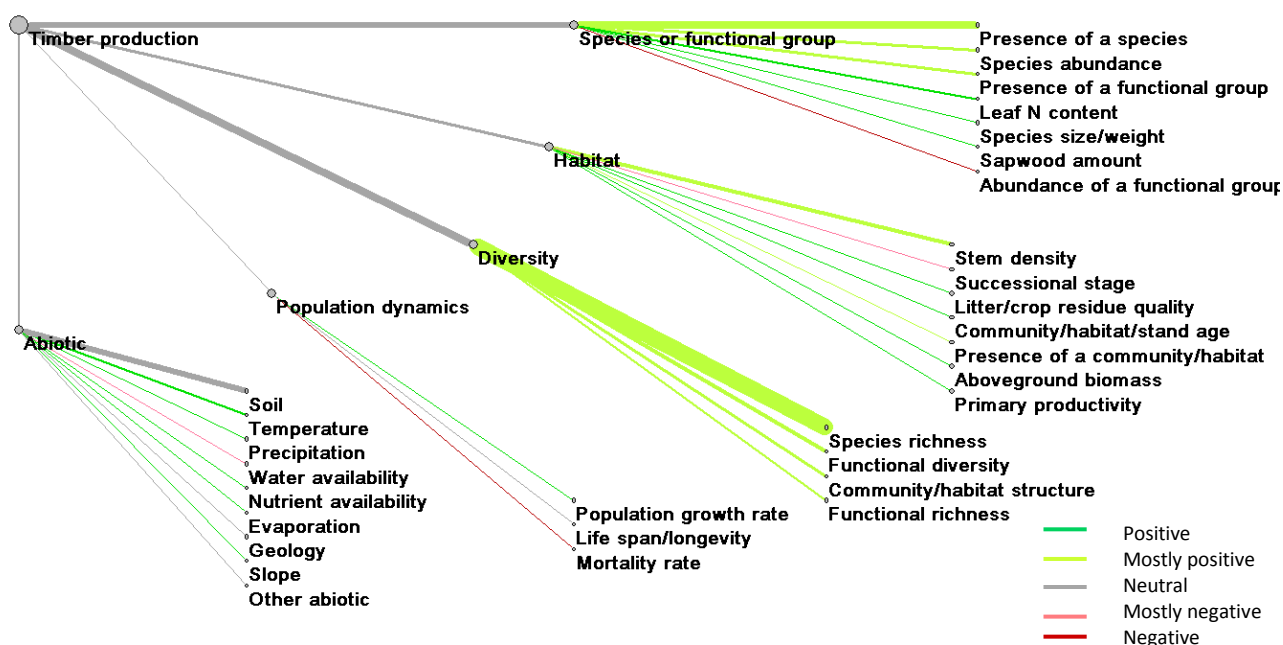


Figure S11. Network diagram mapping the evidence on how biotic attributes and abiotic factors influence the service of timber production. Line thickness is proportional to number of studies supporting each link and line colour indicates predominant direction of link

2.2.3 Food crop production

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.

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.

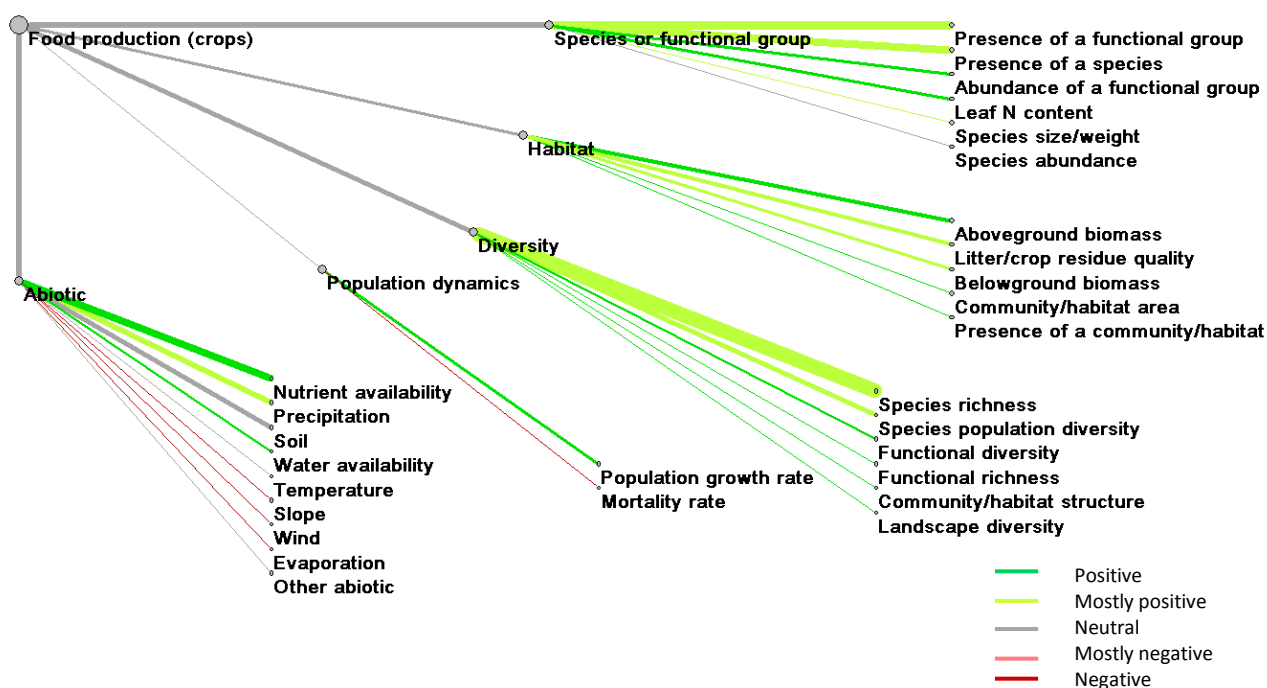


Figure S12. Network diagram mapping the evidence on how biotic attributes and abiotic factors influence the service of food crop production. Line thickness is proportional to number of studies supporting each link and line colour indicates predominant direction of link.

2.2.4 Water supply

Water supply (

Figure S13) is more similar to the regulating services than to the other provisioning services discussed here, because it depends largely on the entire community/habitat area rather than on species characteristics. However, in contrast to the other ecosystem services, the impact of biotic attributes is often negative. Although the interception of rainwater and absorption of groundwater by forests is beneficial for flood protection, as described above, it can also reduce water supply, which can cause problems where water is scarce. Most (42 out of 60) of the articles reviewed describe the negative effects of forests on water supply in water-scarce countries such as Australia and South Africa, although these are typically timber plantations of fast-growing non-native species such as pine or eucalyptus. Community/habitat area, presence of a community/habitat (forest), and stand age all tend to have negative impacts, as older/larger trees use more water (e.g. Noretto et al., 2005), although Cavaleri and Sack (2010) found that forests used more water at earlier successional stages due to faster growth. 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).

In natural forests, 7 studies find beneficial impacts on water supply, with four showing how cloud forests intercept water from the air (e.g. Gomez-Peralta et al. 2008, Brauman et al. 2010) and three showing how forests can increase water yield by improving infiltration and soil water storage capacity (e.g. Singh and Mishra, 2012). Some studies show that native forests consume less water than pine plantations (Rowe and Pearce, 1994; Komatsu, 2008).

For the abiotic factors the situation is largely reversed compared to the service of flood protection, with precipitation and water availability having positive impacts and evaporation (i.e. transpiration) negative impacts.

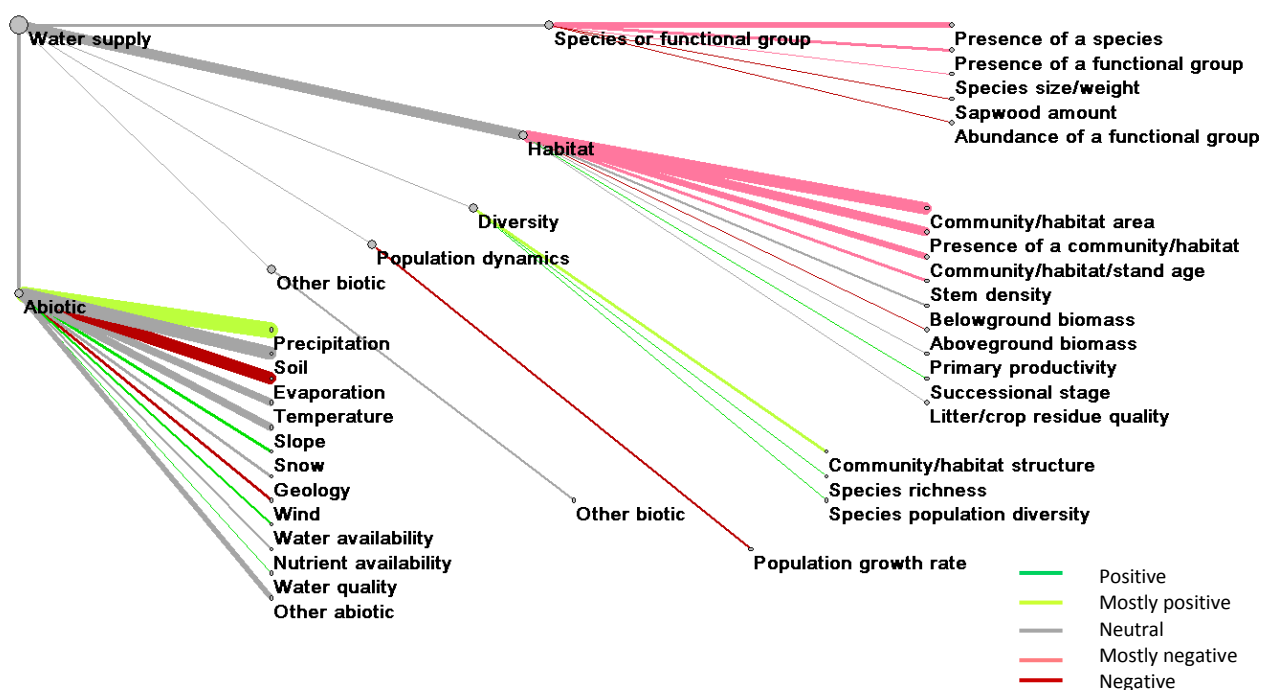


Figure S13. Network diagram mapping the evidence on how biotic attributes and abiotic factors influence the service of water supply. Line thickness is proportional to number of studies supporting each link and line colour indicates predominant direction of link.

2.3 Cultural services

2.3.1 Species-based recreation

For species-based recreation (e.g. wildlife viewing, hunting or fishing), as shown in Figure S13, the most frequently cited 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 by visitors. 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. Clearly the presence of suitable habitat to support the species of interest is important, though this is mentioned less frequently in the literature.

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).

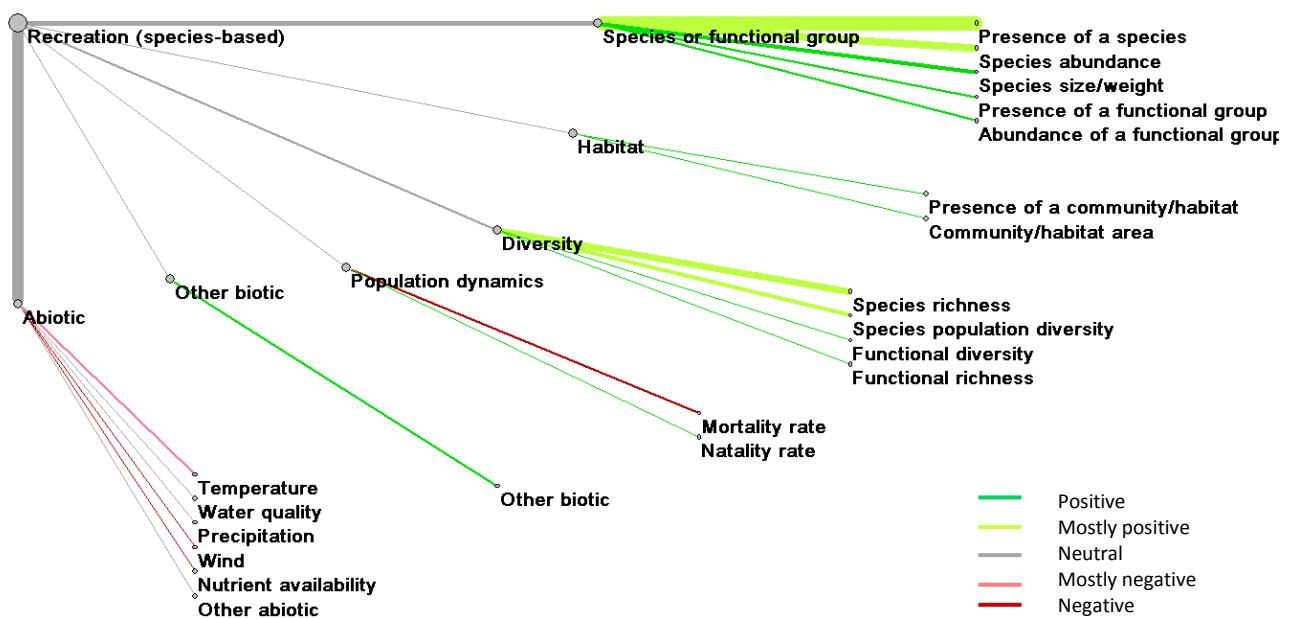


Figure S14. Network diagram mapping the evidence on how biotic attributes and abiotic factors influence the service of species-based recreation. Line thickness is proportional to number of studies supporting each link and line colour indicates predominant direction of link.

2.3.2 Aesthetic landscapes

For aesthetic landscapes (Figure S12) the service is provided by the entire habitat. The presence of a particular habitat is cited in 30 of the 60 papers, with forests and water features being most often mentioned, as well as urban trees and green space (e.g. Kaplan, 2007). Habitat structure is the most frequently cited attribute, with the term 'structure' being interpreted as covering a broad range of characteristics including landscape diversity and complexity, vegetation density, naturalness and uniqueness. Many studies find a preference for wilder, more complex, more natural landscapes (e.g. Acar and Sakici, 2008; Heyman, 2012; Daniel et al., 2012), especially in developed countries, but some cultural groups may prefer more open, managed landscapes with man-made elements. Abiotic attributes that are positively correlated with aesthetic appreciation are the presence of water (lakes and rivers) and steep slopes, which add interest and variety to the landscape

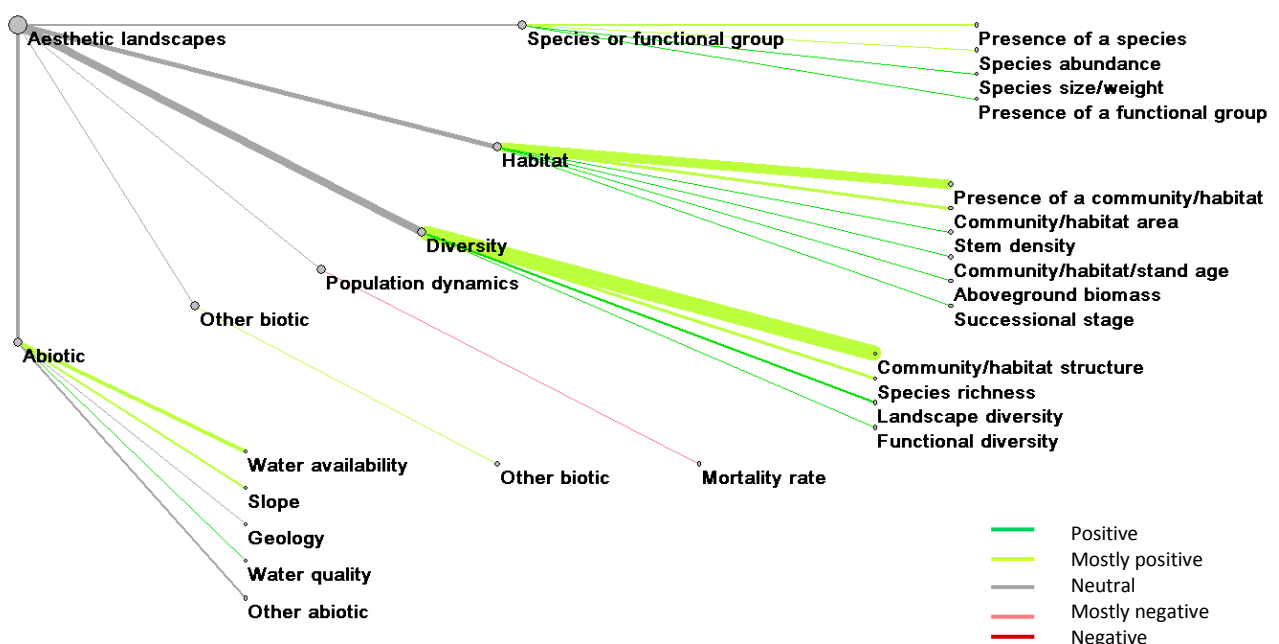


Figure S15. Network diagram mapping the evidence on how biotic attributes and abiotic factors influence the service of aesthetic landscapes. Line thickness is proportional to number of studies supporting each link and line colour indicates predominant direction of link.

3 Ecosystem service providers (ESPs)

The ESP is a useful concept for researchers working on ecosystem services, but it is rarely stated explicitly in the articles reviewed, even when literature refers to the ecosystem service concept. More often, the ESP was inferred by the reviewer from the information given in the article. It is also partly determined by the design and framing of each study, i.e. whether the researchers choose to investigate the role of one or more species, functional groups or entire communities, rather than by the ecosystem components required to provide the service.

Nevertheless, some strong patterns emerge in the ESPs studied for each ecosystem service (Figure S16). Studies of food crop, fish and timber provision generally compare the performance of different species. In contrast, studies of water supply and atmospheric, water flow and water quality regulation focus mainly on comparisons of two or more habitats, e.g. forest and grassland. Studies of mass flow regulation are split between those looking at the entire habitat and those comparing species characteristics, such as root structure. For pollination and pest regulation, the focus is typically on one or more functional groups (such as wasps, bees or pest predators in general), and this is also true for air quality regulation where the functional groups are usually 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 the entire habitat.

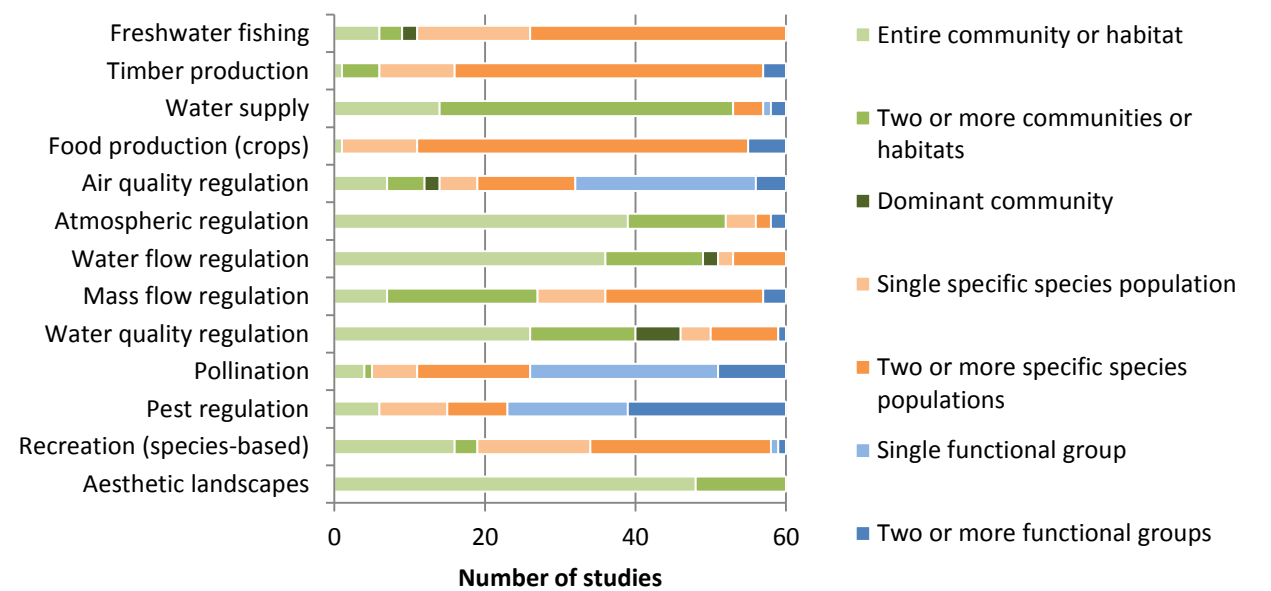


Figure S16: Number of studies showing a linkage between a specific ESP and ecosystem services.

4 Abiotic factors

Table S1: 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 S2: 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

5 Typology

Figure S17 Pathways by which groups of natural capital attributes deliver bundles of ecosystem services

Cell values are the number of papers in the review (out of 60 per ecosystem service) that support a positive (green shading) or negative (red shading and – sign) link between an ecosystem service and a biotic attribute of natural capital. Darker shades indicate more papers supporting the link.

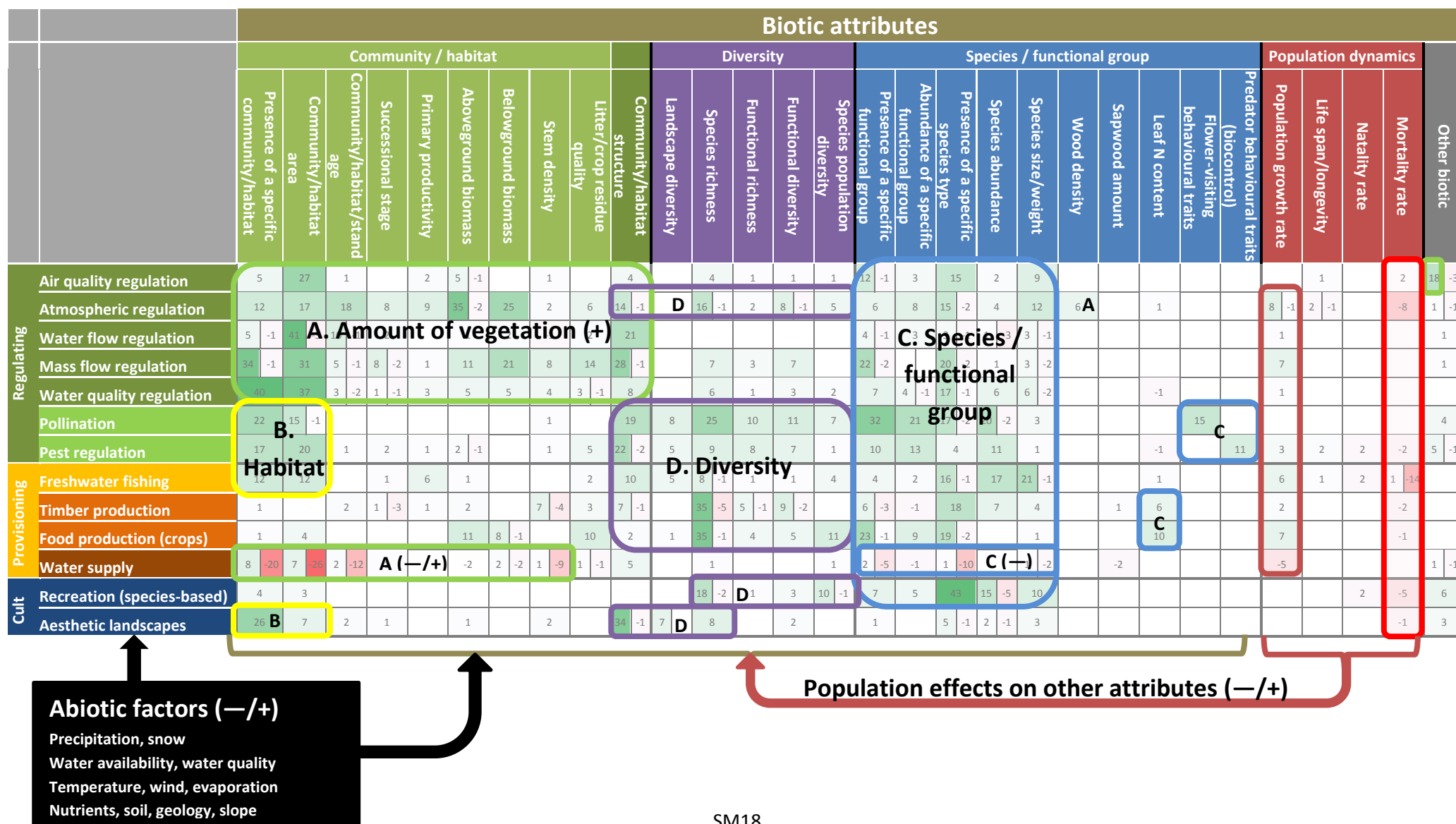


Figure S18 Summary schematic diagram of pathways by which groups of natural capital attributes deliver bundles of ecosystem services

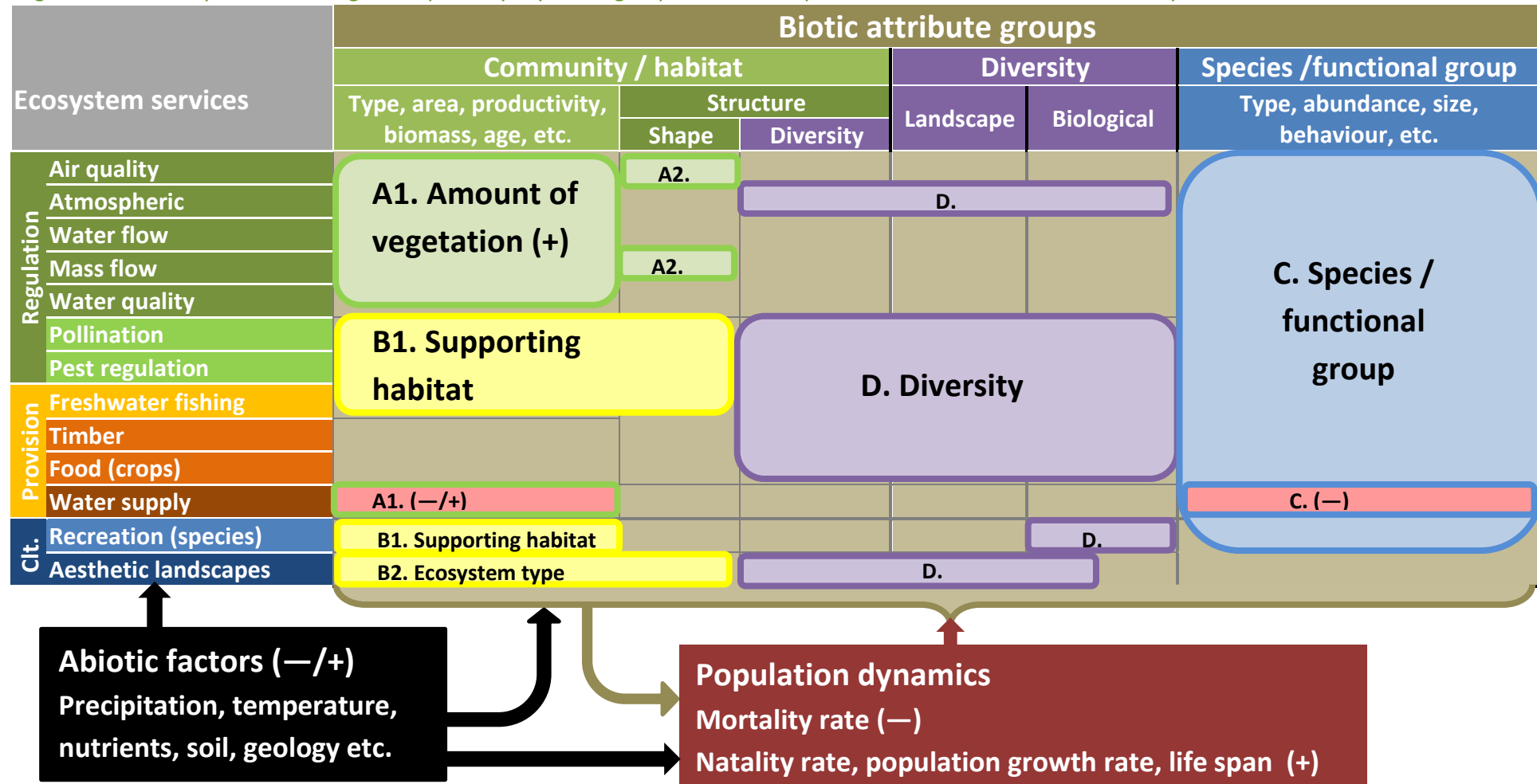
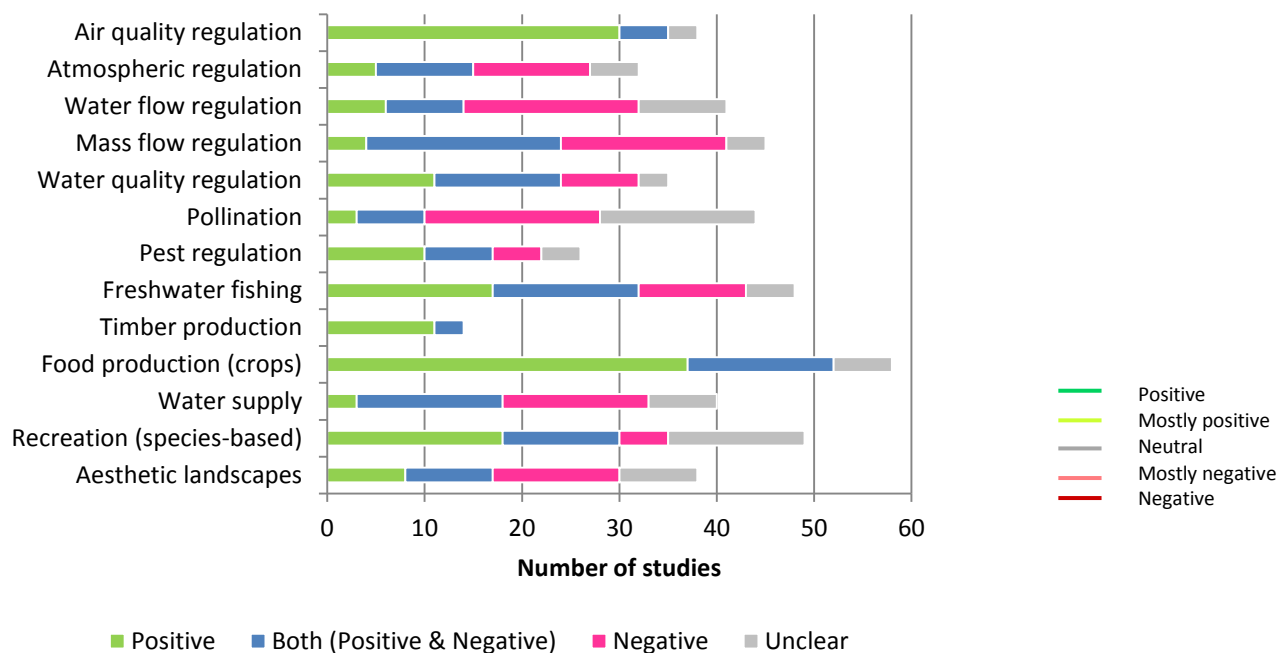


Figure S19. Impact (direction) of human input and management for each ecosystem service reviewed.



Appendix A: Search terms for the systematic literature search

Standard set of terms related to biotic attributes

*diversity OR *diverse OR species OR habitat* OR trait* OR landscape OR richness OR abundance

Note: "OR mix*" was also used for timber production to cover species mixtures.

Service-specific terms

Ecosystem service	Ecosystem service terms	Additional terms used to refine results
Freshwater fishing	(*fish*) AND (yield OR catch OR quantity OR 'ecosystem service' OR producti*)	(freshwater OR lake* OR river* OR reservoir* OR floodplain* OR inland)
Timber production	forestry OR plantation* OR timber OR wood	Yield OR producti* OR growth OR supply OR harvest OR "basal area"
Water supply	(water OR freshwater OR groundwater) AND (supply OR provision* OR yield OR budget OR reserve* OR resource*)	(*forest* OR soil OR vegetat* OR ecosystem* OR woodland*) AND (infiltrat* OR recharg* OR runoff)
Food production (crops)	TOPIC: (Food OR crop OR agricultur*) AND TITLE: (Producti* OR yield)	NOT TITLE: grassland OR meadow OR graz* OR pasture OR aquatic OR *alga* OR fish* OR milk OR dairy OR biofuel OR bioenergy OR biodiesel OR miscanthus OR bioethanol OR *foram* OR *benth* OR *plank* OR pest OR pollin* OR predat* OR bird*
Air quality regulation	"air quality" OR "air pollution" OR particulate*	(tree* OR vegetation OR forest* OR wood*) AND (absor* OR remov* OR regulat* OR adsor*)
Atmospheric regulation (carbon storage)	"Carbon storage" OR "carbon sequestration" OR "carbon loss" OR "carbon emissions"	Tree* OR soil* OR biomass
Water flow regulation (flood protection)	Flood* OR "water flow regulation"	(Flow* OR Attenuation OR Storage OR Protection OR Defence OR Prevention OR Runoff OR Evapotranspiration OR Infiltration OR interception) AND (vegetation OR forest OR wetland OR marsh)
Water quality regulation	Water quality OR Water regulation OR Water purification OR Nutrient* retention OR Nutrient* translocation	Tree* OR Soil* OR Forest* OR Vegetation OR Plant* OR Pollutant* OR Wetland* OR Microorganism* OR Accumulation OR Sediment*
Mass flow regulation (erosion protection)	soil OR sediment OR sand AND	Root OR vegetation

Ecosystem service	Ecosystem service terms	Additional terms used to refine results
	loss OR erosion OR trap* OR runoff OR stabil* OR erodab*	
Pollination	Pollinat*	yield OR Fruit OR "Seed set" OR reproduct*
Pest regulation	"Natural pest control" OR "Pest control" OR "Biological control" OR "Biological pest control"	
Species-based recreation	"species-based recreation" OR eco-tourism OR *watching OR viewing OR birding OR "nature tourism"	satisf* OR visit* OR appreciat* OR motivate* OR prefer*
Aesthetic landscapes	tourism OR recreation OR *esthetic* OR appreciation OR valuation OR preference* OR perception*	

Appendix B: List of biotic and abiotic attributes covered in the review

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 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 (attributes not covered in the list can be added and described in the free text box)

ABIOTIC ATTRIBUTES

- Temperature (a positive relationship indicates that the ecosystem delivers a higher level of service when temperatures are higher)
- Precipitation (a positive relationship indicates that the ecosystem delivers a higher level of service when precipitation is greater)
- Snow (a positive relationship indicates that the ecosystem delivers a higher level of service when there is more snowfall)
- Water availability – the amount of water available in the ecosystem to be used by organisms or for aesthetic appreciation by humans (a positive relationship indicates that the ecosystem delivers a higher level of service when water availability is greater)
- Evaporation (a positive relationship indicates that the ecosystem delivers a higher level of service when evaporation – including evapo-transpiration - is greater)
- Wind (a positive relationship indicates that the ecosystem delivers a higher level of service when wind speed or duration of windy periods are higher)
- Water quality – (a positive relationship indicates that the ecosystem delivers a higher level of service when water quality is higher, i.e. water is cleaner and less polluted)
- Nutrient availability (a positive relationship indicates that the ecosystem delivers a higher level of service when nutrient availability is greater)
- Soil – this is a categorical variable based on soil type and a bundle of other factors including porosity, acidity and water content, so it is meaningless to ascribe a single direction of impact and all impacts are recorded as 'unclear'
- Geology - this is a categorical variable based on rock type, topology and other factors such as porosity and permeability, so it is meaningless to ascribe a single direction of impact and all impacts are recorded as 'unclear'
- Slope – angle of inclination of the landform (a positive relationship indicates that the ecosystem delivers a higher level of service when slopes are steeper)
- Other – any abiotic factors not included in the list above can be added and described in the free text box. As this covers a broad range of factors, it is meaningless to ascribe a direction of impact and all impacts are recorded as 'unclear'.

Appendix C: Main indicators used in the literature for each service (with typical units)

Freshwater fishing

- Catch/ yield (kg/ha/year)
- Catch per unit effort
- Fish size/weight
- Growth rate (kg/year)
- Fish population
- Mortality rate
- Willingness to pay for a better fishing service

Timber production

- Yield (tonnes/ha/year; m³/ha/year)
- Basal area (m²/ha)
- Height (m) and diameter at breast height (m) of trees
- Growth rate (tonnes/ha/y; m²/ha/year; mean annual increment of diameter at breast height or basal area)
- Timber quality and tree health (qualitative)
- Sapling survival rates
- Profit from timber sales (\$)

Water supply

- Water supply (m³/ha/year)
- Runoff from watershed (m³/year; mm)
- Evapotranspiration (mm/year)
- Stream height; low flow (mm)

Food production (cultivated crops)

- Crop yield (tonnes/ha; kg/household)
- Crop value (\$/ha)

Air quality regulation

- Change in pollutant concentration (g/m³; ppm)
- Pollutants removed (kg/ha/year; kg/year; g/tree; g/cm² leaf area)
- Deposition rates (mg/m²)
- Deposition velocity (m/s)
- Leaf area index
- Particle trapping efficiency (%)
- BVOC (biogenic volatile organic compound) emission factors

Atmospheric regulation (carbon sequestration)

- Carbon storage in soil and/or vegetation (Mt/ha)

- Carbon sequestration (Mt/ha/year)
- Soil carbon content (%)

Mass flow regulation (erosion protection)

- Soil erosion (t/ha/year; g/l run-off; g/m²; g/hour; mm)
- Soil retention (t/year; t/ha; g/cm³)

Water flow regulation (flood protection)

- Peak flow (m³/s)
- River depth / flood height (m)
- Surface water runoff (l/m²/minute; mm)
- Wave height attenuation (m)
- Flood frequency and severity (e.g. number of people displaced)
- Water velocity (m/s)

Water quality regulation

- Concentrations of pollutants (nitrogen; phosphorous; suspended solids; heavy metals) (g/m³)
- Water characteristics (clarity; dissolved oxygen; biological oxygen demand; chemical oxygen demand; pH)
- Nutrient removal or retention (g/y; % removed)
- Enrichment factor of pollutants in roots and shoots
- Ecological quality (qualitative assessment; plankton richness and abundance; species diversity)

Pollination

- Pollinator abundance (number/ha)
- Pollinator diversity (species richness; diversity index)
- Pollinator visitation rates (number/flower/hour; number/hour)
- Pollination efficiency (% flowers pollinated)
- Plant reproductive success (fruit set per plant; seed set per fruit)
- Crop yield (t/ha)
- Pollen grain deposition (grains/visit; grains/day)
- Value of pollinated crop (\$/ha)
- Replacement cost of pollination (by non-insect means) (\$/ha)

Pest regulation

- Pest abundance / density (number / plant; number / ha)
- Pest diversity (species richness; diversity index)
- Pest mortality due to predation
- Predator density (number / plant; number / ha)
- Predator diversity (species richness; diversity index)
- Crop damage (number of plants, leaves or fruits damaged)
- Crop yield (t/ha)
- Value of natural pest control (\$/ha/year)

Recreation (species-based)

- Visitor numbers
- Frequency of visit
- Length of trip (hours; days)
- Visitor expenditure (\$/capita; \$/trip; \$/year)
- Economic revenues from activities (\$/year)
- Travel cost (\$/trip; \$/capita)
- Visitor satisfaction
- Visitor preferences
- Willingness to pay (\$)
- Species abundance
- Species richness
- Frequency of species sightings
- Success rate of hunting trips
- Catch per unit effort for fishing
- Species reproductive success
- Species mortality rate
- Employment
- Recreation/ecotourism opportunities

Aesthetic landscapes

- Landscape preferences (ranking / prioritisation)
- Rating of qualities such as scenic beauty, naturalness, wilderness, recreational opportunities (point scale)
- Willingness to pay (\$)
- Property values (\$)
- Visitation rates

Appendix D: List of papers reviewed

Air quality regulation

- Al-Dabbous, A.N., Kumar, P. (2014) The influence of roadside vegetation barriers on airborne nanoparticles and pedestrians exposure under varying wind conditions. *Atmos. Environ.* 90, 113e124.
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<http://dx.doi.org/10.1016/j.envpol.2010.12.005>.
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- Cardelino, C. A.; Chameides, W. L. (1990) Natural hydrocarbons, urbanization, and urban ozone. *Journal of Geophysical Research* 95 (D9): 13971-13979. 10.1029/JD095iD09p13971

- Cavanagh, J. A. E.; Zawar-Reza, P.; Wilson, J. G. (2009) Spatial attenuation of ambient particulate matter air pollution within an urbanised native forest patch. *Urban Forestry & Urban Greening* 8: 21-30. 10.1016/j.ufug.2008.10.002
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