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A visualization platform to analyze contextual links between natural capital and ecosystem services

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ABSTRACT

To prevent further loss of our vital ecosystem services we must understand the linkages to their supporting natural capital attributes. Systematic literature reviews synthesise evidence of natural capital attribute to ecosystem service (NC-ES) linkages. However, such reviews rarely account for the context dependency of evidence that is derived from individual studies undertaken for a particular purpose, at a specific spatial scale or geographic location. To address this deficiency, we developed the LiNCAGES (Linking Natural Capital Attribute Groups to Ecosystem Services) platform for investigating the context dependency of literature-based evidence for NC-ES linkages. We demonstrate the application of the LiNCAGES platform using the OpenNESS systematic literature review of NC-ES linkages. A hypothetical use case scenario of a small-scale European forest manager is described. We find evidence for many NC-ES linkages, and trade-offs and synergies between services, is severely diminished or non-existent under certain contexts, such as larger spatial scales and European study location. The LiNCAGES platform provides a flexible tool that researchers can use to support collation, exploration and synthesis of literature-based evidence on NC-ES linkages. This is vital for providing credible and salient evidence to stakeholders on important NC-ES linkages that occur under their context, to guide effective management strategies.

1. Introduction

Natural capital is the world's stock of natural assets, which supplies a wide range of ecosystem services that directly or indirectly produce value for people (Smith et al., 2017). Ecosystem services are vital for human existence and good quality of life, yet global indicators of ecosystem extent and condition have declined by 47%, relative to their earliest estimated states (Díaz et al., 2019). This is likely to have repercussions for ecosystem services. To prevent further loss of ecosystem services we must understand how they are influenced by attributes of natural capital (de Bello et al., 2010; Díaz et al., 2019; Harrison et al., 2014; Ricketts et al., 2016), so that manageable natural capital attributes that are essential for ecosystem service delivery can be identified (Harrison et al., 2014; Maseyk et al., 2017). However, due to their broad and complex nature, investigation of natural capital attribute to ecosystem service (NC-ES) linkages must incorporate a holistic approach and account for context dependency (Adhikari and Hartemink, 2016; Gutierrez-Arellano and Mulligan, 2018; Harrison et al., 2014).

Holistic investigation is important as an attribute of natural capital can support the provision of one ecosystem service, while at the same time antagonising another service (Harrison et al., 2014; Maseyk et al., 2017). Furthermore, ecosystem services themselves can interact with each other both positively and negatively, as some regulating ecosystem services underpin the delivery of other services, particularly provisioning services (Boerema et al., 2017; Raffaelli, 2006; Ziter, 2016). For example, pollination is critical for the delivery of food production (Harrison et al., 2014). However, using land for food production reduces or removes the provision of some regulating and cultural services, such as atmospheric regulation, erosion control, air and water quality regulation and recreation that would be provided if the land were forested (Maes et al., 2012).

Many of the NC-ES linkages evidenced in the literature are highly context dependent (Adhikari and Hartemink, 2016; Harrison et al., 2014). This context dependency includes aspects such as ecosystem type, spatial and temporal scale, geographical location and study method.

Ecosystem type influences NC-ES linkages (Feld et al., 2009; Hevia et al., 2017; Maskell et al., 2013). For example, urban forests typically store about half as much carbon as natural forests, so are less effective in providing the ecosystem service of atmospheric regulation (Zhao et al., 2010). This is thought to be due to their younger age structure (Zhao et al., 2010). NC-ES linkages are influenced by the spatial scale at which the natural capital attributes operate and the scale at which the ecosystem service is

Abbreviations: LiNCAGES, Linking Natural Capital Attribute Groups to Ecosystem Services; NC-ES, natural capital to ecosystem services

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delivered (Burkhard et al., 2012; de Bello et al., 2010; Haines-Young and Potschin, 2011; Hevia et al., 2017; Maskell et al., 2013; Raffaelli, 2006). Duncan et al. (2015) found that assessing NC-ES linkages at large spatial scales resulted in significant information loss of the mechanisms underpinning NC-ES linkages, as key ecosystem functions work at finer scales. Additionally, Ricketts et al. (2016) found that broader spatial scale studies might evidence more positive NC-ES linkages as they capture a greater variation of natural capital attributes. The temporal scale of a study has also been shown to influence NC-ES linkages (Cimon-Morin et al., 2013). For example, different pollinator species begin flight at different times in the day due to differing body size, warm-up rates and ambient flight temperature (Kremen, 2005). As a result, coarser temporal scales may not capture the influence of some of these species on pollination services. Experiment type has also been known to affect NC-ES linkages, with Balvanera et al. (2006) finding more positive NC-ES linkages where environmental variables could be controlled best, such as greenhouse experiments.

These context dependent aspects also interact with each other. For example, the ecosystem type under investigation can affect study temporal scale, e.g., due to the difficulty in maintaining experimental setup in a hostile environment (Raffaelli, 2006). The aspects are also influenced by other pragmatic factors such as the time available in a research studentship or grant (Martnez-Harms and Balvanera, 2012; Raffaelli, 2006), the maximum plot size that could be handled by the researcher, and the space available for the work (Raffaelli, 2006). These limitations lead to the completion of experimental NC-ES studies mostly at small scales, with the larger scale studies using secondary source evidence and modelling (Martnez-Harms and Balvanera, 2012).

The context dependency of evidence on NC-ES linkages is not explored in many studies (Duncan et al., 2015), making the transferability of empirical evidence and its synthesis, difficult. Furthermore, evidence for NC-ES linkages in the literature is highly fragmented (de Bello et al., 2010; Smith et al., 2017) and can be difficult to locate through standard search engines due to the vagueness and imprecision of ecosystem service definitions (Boerema et al., 2017; Englund et al., 2017). While it can be argued that this encourages creativity and transdisciplinary collaboration, it also leads to difficulty in finding and synthesising relevant information from the literature (Boerema et al., 2017).

Previous studies have attempted to overcome these limitations and synthesise the literature on NC-ES linkages using systematic review methodologies. However, the majority of these studies fail to incorporate a holistic approach by focussing on individual ecosystem functions, taxonomic groups or ecosystem services (Gutierrez-Arellano and Mulligan, 2018; Harrison et al., 2014; Lefcheck et al., 2015; Ziter, 2016). Most studies focus on species level natural capital attributes, yet functional group and population level natural capital attributes are also vital for underpinning the supply of ecosystem services (Ricketts et al., 2016).

Seven systematic reviews attempted to be more holistic in their design: Balvanera et al. (2006), de Bello et al. (2010), Harrison et al. (2014), Hevia et al. (2017), Ricketts et al. (2016), Schwarz et al. (2017) and Smith et al. (2017). For comparison of these reviews, see Supplementary Material Table S1. The number of studies used in the systematic reviews varies considerably from 103 in Balvanera et al. (2006) to 780 in Smith et al. (2017), as do the number of ecosystem services investigated from four in Ricketts et al. (2016) to 13 in both Smith et al. (2017) and Hevia et al. (2017). Some reviews were limited to a specific ecosystem, e.g. Schwarz et al. (2017) focused on urban environments, and some reviews recorded significantly more study aspects that could identify context dependency, with the greatest amount recorded by Smith et al. (2017). See Supplementary Material Section 4 for study aspects recorded by Smith et al. (2017).

These reviews use a variety of methods from vote counting to meta analysis, with the majority favouring some form of vote counting approach due to the widely varying disciplines involved in NC-ES research (Smith et al., 2017). This vote counting aproach is a major limitation, as it assumes equal contribution of evidence from the studies. Admittedly de Bello et al. (2010) and Hevia et al. (2017) did filter for studies that showed significant linkages. Harrison et al. (2014) attempted to add a strength of evidence parameter to the NC-ES linkages that were extracted from the studies they considered, but this was later abandoned by Smith et al. (2017), who reverted to vote counting when building on this work due to the use of many incompatible indicators and approaches in the literature base. However, Smith et al. (2017) did not attempt to account for the context of the NC-ES linkages when assigning a weight to the evidence provided by a particular study. This is most likely due to the subjectivity of the context of a NC-ES linkage, as certain contexts may be more useful for specific research or stakeholder questions.

This study aims to address these limitations by building on the work of Smith et al. (2017) through developing a platform for Linking Natural Capital Attribute Groups to Ecosystem Services (LiNCAGES). LiNCAGES aims to support the dialogue between science and policy by improving stakeholder's understanding of important natural capital to ecosystem service linkages, and associated trade-offs and synergies, relevant to their own context. Thus, it provides scientific evidence that is more salient to their needs. For example, a local landowner may prefer to use evidence from local scale studies from a similar landscape, whilst a policy-maker may prefer national scale studies covering multiple ecosystems. LiNCAGES also aims to provide a resource for researchers by enabling consistent collation of the fragmented knowledge base on natural capital and ecosystem services, to identify key gaps in evidence. This fosters collaborative working, to target and collate additional evidence that can strengthen the sustainable management of natural capital for the benefit of people and biodiversity. This paper describes the development and features of the LiNCAGES platform and its application to a hypothetical use case.

2. Methods

The LiNCAGES platform (available at: https://shiny-apps.ceh.ac.uk/LiNCAGES/) was developed and tested using the Operationalisation of Natural Capital and Ecosystem Services (OpenNESS) database (Smith et al., 2017). We chose OpenNESS as it provides a recent and substantial evidence base pertaining to a wide range of ecosystem services and natural capital attributes, in addition to recording the largest amount of context dependent aspects of all of the review studies we considered. The OpenNESS database consists of a systematic literature search of 780 peer-reviewed journal articles published in the English language across 13 ecosystem services, targeting 60 papers per ecosystem service. It used a standardised protocol based on customized keywords developed by Harrison et al. (2014) and covered articles published up until the end of June 2014 (Pérez-Soba et al., 2017; Smith et al., 2017). See Supplementary Material Section 2 for the list of key words used to create the OpenNESS database. Some journal articles were split into multiple studies if they addressed more than one ecosystem, location or ecosystem service, and were entered separately into the database (Pérez-Soba et al., 2017).

The database includes: four provisioning ecosystem services (food production (crops), freshwater fishing, timber production, water supply); seven regulating ecosystem 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 ecosystem services (species-based recreation and aesthetic landscapes) (Pérez-Soba et al., 2017). For each article, the reviewer recorded the direction of each of the linkages between the ecosystem service the study was investigating and 42 natural capital attributes (30 biotic and 12 abiotic). See Supplementary Material Section 3 for a list of all the natural capital attributes and their definitions. The reviewer classified each of these 42 NC-ES linkages as positive, negative, unclear, both (positive and negative), or not mentioned. An unclear linkage direction was assigned when the study mentions that the ecosystem service is affected but does not give an indication of the direction. To avoid confusion for the user of the LiNCAGES platform, we grouped "unclear" and "both (positive and negative)" linkage directions underneath the umbrella term of "unclear". The OpenNESS database classified the natural capital attributes of soil and geology as categorical and therefore they could not be assigned a direction of relationship, so the direction of NC-ES linkages with these natural capital attributes were classified as unclear (Pérez-Soba et al., 2017).

In this use case scenario, we investigate the context dependency of the study aspects: spatial scale, temporal scale and location as an example, though the LiNCAGES platform can be used to investigate a further 13 context dependent aspects present in the OpenNESS database. For all the context dependent study aspects available in the LiNCAGES platform, see Supplementary Material Section 4.

The LiNCAGES platform accounts for these context dependent study

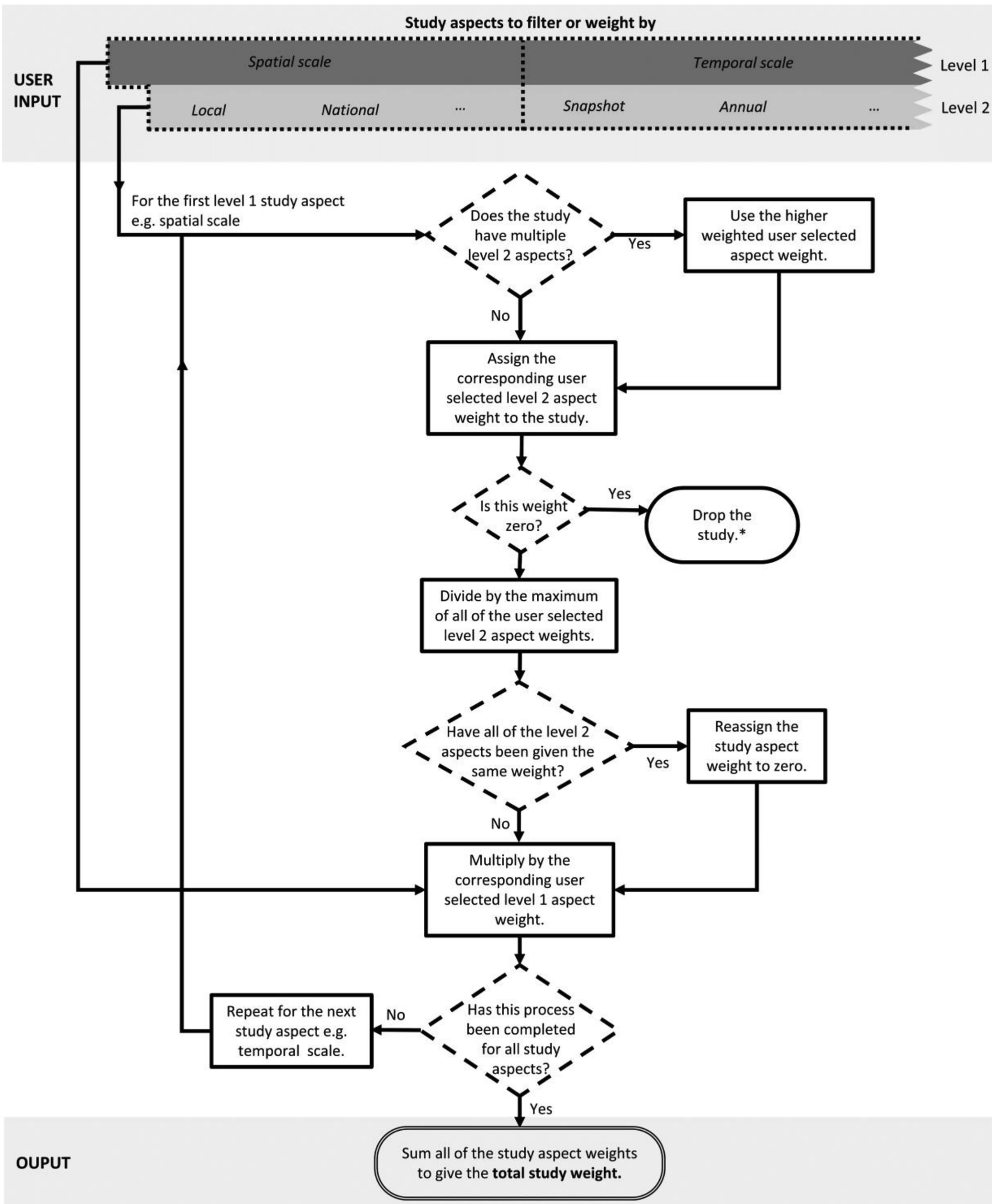

Fig. 1. Method flowchart used by the LiNCAGES platform for filtering and hierarchically weighting the studies. The user input section features a visual representation of the two-tier hierarchical weighting system used in the LiNCAGES platform. The torn effect on the right-hand side of the user input section indicates that the hierarchy continues to include a further 14 level 1 aspects. Likewise, the level 2 aspect box with "…" indicates that there are actually more level 2 aspects to weight by than are shown in this visual representation. **Assigning '0' to an aspect indicates the user wishes to filter out articles featuring that level 2 aspect.*

aspects by allowing the user to filter or weight them according to their needs. Filtering allows the user to remove all the studies that feature a certain aspect and then create visualisations from the filtered studies. If a study contains multiple options for the same study aspect, e.g. where it spans multiple continents, the LiNCAGES platform will only filter out the study once the user has chosen to filter all of the options it contains. In cases where filtering may be considered too strict, for example when the user wishes to prioritise certain types of studies above others, but not lose studies entirely, which would reduce their sample size, weighting can be used. Weighting allows the user to attach greater importance to specific contexts using a two-tier hierarchical weighting system, described visually in the user input section of Fig. 1. For hierarchical weighting the user weights the level 2 aspects (e.g. 'local', 'national') relative to each other and then assigns an overall weight (level 1 aspect weight) to their level 2 weighting choices for each of the level 1 aspects (e.g. spatial scale, temporal scale). The total weight of the study is then calculated as shown by the method flowchart in Fig. 1; see also Supplementary Material Section 5 for a worked example of calculating the total study weight based on example user assigned weights. To help inform the definition of weights, the LiNCAGES platform shows the frequency of studies that feature each context dependent study aspect.

The total study weight is assigned to all of the NC-ES linkages for which that study provides evidence. This process is repeated for all studies included in the OpenNESS database. Then the sum of all of the study weights that support each of the included NC-ES linkages is calculated and can be visualised as either a stacked bar plot or network diagram.

The network diagrams produced by the LiNCAGES platform are fully interactive and allow the user to select particular NC-ES linkages and extract references for all of the studies that evidence that linkage. Selecting a node (ecosystem service or natural capital attribute) in the network diagram will output a reference table of all of the evidence for NC-ES linkages with that node. If the user has chosen to weight by particular context aspects, these references are ordered by their total weight, allowing the user to identify which studies are more relevant to their chosen context (Table S2). The user can also download a more detailed breakdown of how the weights for each of the studies have been calculated from their chosen weightings (Table S3). A weighted network diagram (Fig. S5) and extracted references for a NC-ES linkage (Table S2) can be found in the weighting and filtering worked example in Supplementary Material Section 5.

LiNCAGES has been strongly informed by both stakeholder and researcher feedback throughout its development. We demonstrated LiNCAGES using an iPad at a variety of workshops and conferences (Lancaster Local Nature partnership, exhibit stand at The Centre for Global Eco-Innovation's Eco-I conference, Natural Capital Initiative Summit and the Lancaster Environment Centre Spring 2019 conference) to collect feedback on functionality, visualisations and ease of use.

3. Results

We demonstrate the potential applications of the LiNCAGES platform through discussion of a hypothetical use case scenario. A small-scale European forest manager receives benefits from the ecosystem service of timber production. The forest manager wants to use the LiNCAGES platform to discover which attributes of their natural capital they should promote to maximise the benefits they receive from timber production. Throughout this use case scenario, we use bar plots to visualise the NC-ES linkages as feedback on LiNCAGES from stakeholders and researchers was that bar plots were the easiest visualisation option to interpret and understand quickly. However, other visualisation options are available within LiNCAGES (network diagrams (Fig. S5) and radar plots (Fig. S6)) which may be more suitable to certain users or applications.

3.1. NC-ES linkages for one ecosystem service

First, the forest manager uses the LiNCAGES platform to visualise all the evidence for linkages between the 42 natural capital attributes and the ecosystem service of timber production (Fig. 2).

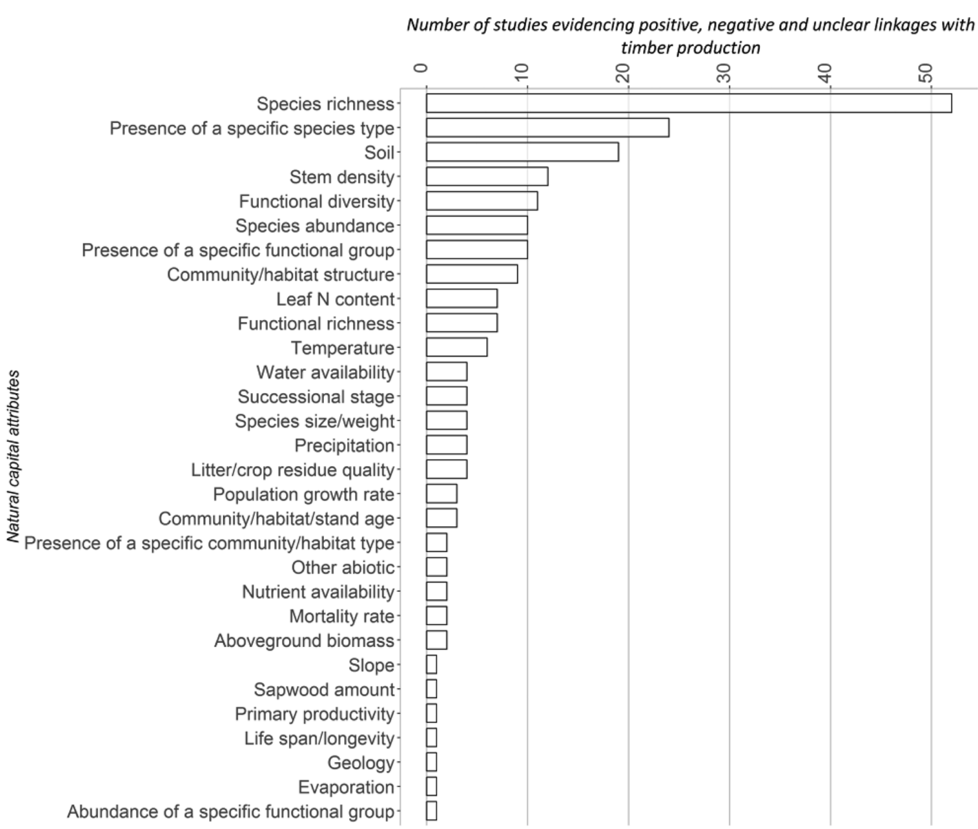

Fig. 2. Bar graph of the number of studies evidencing NC-ES linkages with the ecosystem service of timber production for all directions of linkage (positive, negative and unclear), ordered by number of studies providing evidence. *Natural capital attributes without evidence for NC-ES linkages with timber production are not shown in this figure.*

Fig. 2 shows that timber production has 21 linkages with biotic attributes and nine linkages with abiotic attributes. Species richness has the most evidence for linkages with timber production, followed by presence of a specific species type and soil. Overall, species and functional group level natural capital attributes have the most evidence for linkages with timber production. Fig. 2 shows the amount of evidence for a linkage with timber production; yet does not show whether the linkage is positive or negative. Therefore, we used the LiNCAGES platform to compare the amount of evidence for positive and negative linkage directions (Fig. 3).

Fig. 3 shows that in total, there are 25 positive and 11 negative NC-ES linkages with timber production. By comparing Figs. 2 and 3 we find no evidence for positive or negative linkages for the natural capital attributes of soil and geology because the OpenNESS database classified the direction of these NC-ES linkages as unclear (Pérez-Soba et al., 2017); this highlights the importance of considering the methodology used to extract the evidence supporting the LiNCAGES platform. Species richness and presence of a specific species type have the most evidence for positive linkages with timber production. This is counterintuitive because positive linkages with presence of a specific species type suggests monocultures are best for timber production (e.g. Paquette and Messier, 2011), whereas positive linkages with species richness suggest mixed species forests are best for timber production (e.g. Bristow et al., 2006; Vilà et al., 2013). Fig. 3 shows further uncertainty in the direction of NC-ES linkages; nine of the natural capital attributes have both positive and negative linkages with timber production, with species richness having the most evidence for both positive and negative linkages. Many systematic reviews stop their analysis at this stage (e.g. Balvanera et al., 2006; de Bello et al., 2010; Harrison et al., 2014; Ricketts et al., 2016; Hevia et al., 2017; Schwarz et al., 2017; Smith et al., 2017) and do not investigate this uncertainty in direction.

3.2. Context dependency of NC-ES linkages for one ecosystem service

Context dependency could be responsible for both the uncertainty in direction of the NC-ES linkages and the counterintuitive observations shown by Fig. 3. The forest manager explores the context dependency of the evidence behind the NC-ES linkages with timber production by using the LiNCAGES platform to filter the evidence to three different contexts: (a) evidence from studies with spatial scales larger than local, (b) evidence from studies with a snapshot temporal scale (short term study) and (c) evidence from studies undertaken in Europe. Fig. 4 shows how the amount of evidence for the NC-ES linkages with timber production changes under the three respective contexts, compared to the unfiltered NC-ES linkages in Fig. 3, allowing the forest manager to review the influence of context on both the direction and existence of NC-ES linkages.

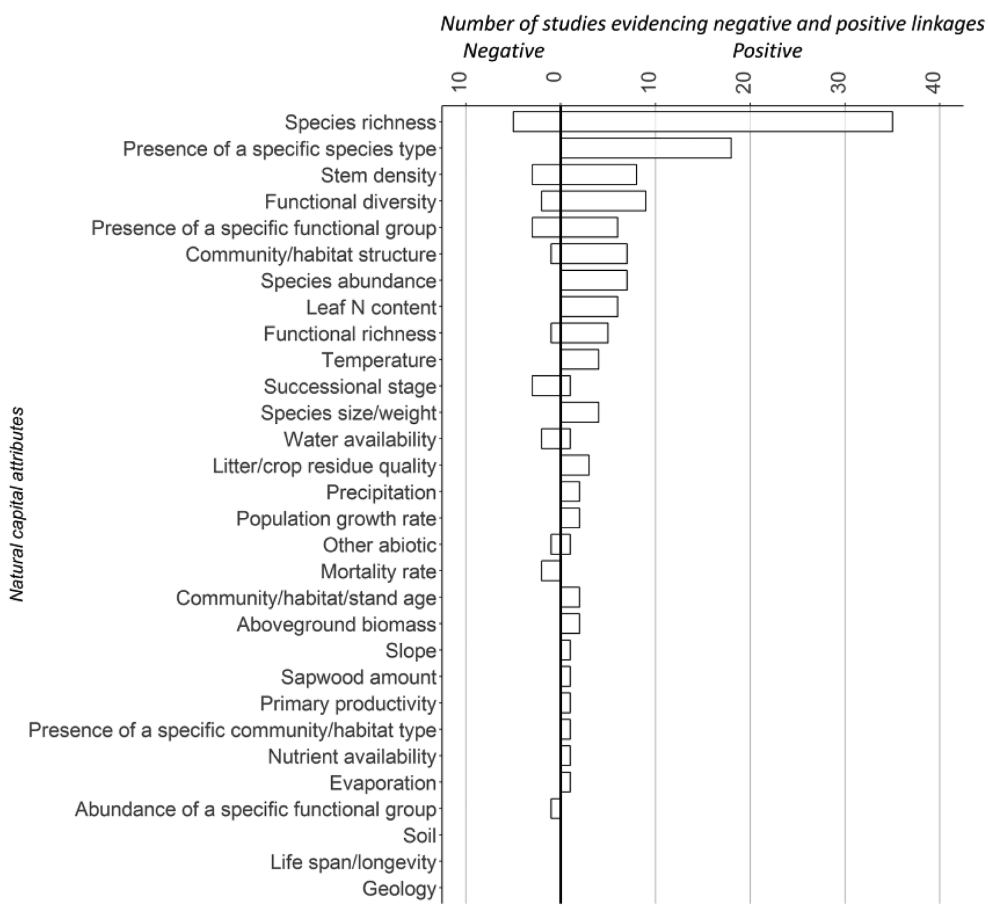

Fig. 3. Mirrored bar graph of positive and negative NC-ES linkages with the ecosystem service of timber production. The number of studies evidencing positive linkages and negative linkages is shown on the positive (right) and negative (left) part of the x-axis respectively.

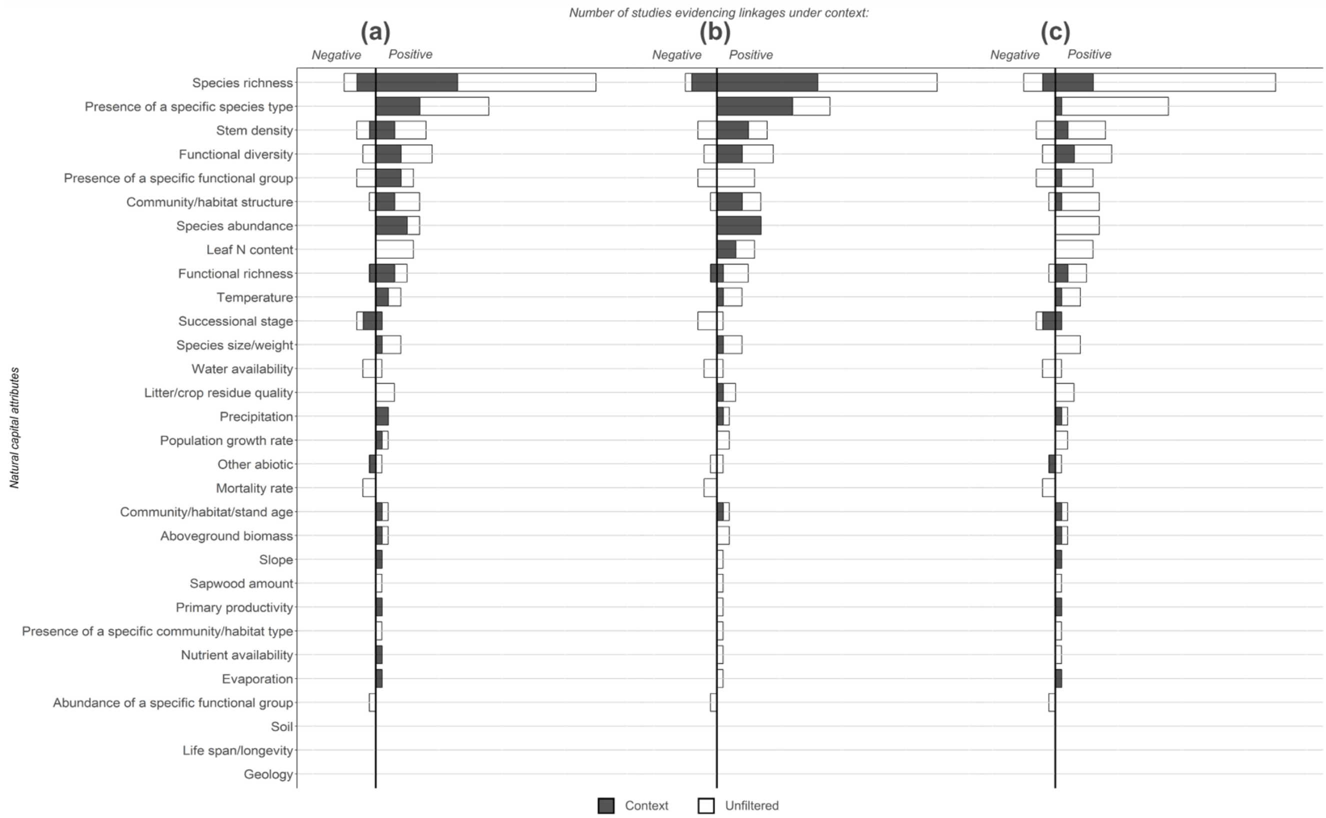

Fig. 4. Mirrored overlay bar graphs showing the positive and negative NC-ES linkages with the ecosystem service of timber production, filtered for three different contexts: (a) evidence from studies with spatial scales larger than local, (b) evidence from studies with a snapshot temporal scale and (c) evidence from studies undertaken in Europe. Evidence for positive and negative NC-ES linkages are shown on the positive (maximum = 35) and negative (maximum = 5) part of the x-axis, respectively. To aid comparison, for each context the filtered NC-ES linkages (dark grey) are overlaid onto the unfiltered NC-ES linkages (white) from Fig. 3.

Fig. 4(a) shows that filtering the evidence for larger spatial scales than local entirely removed evidence for NC-ES linkages for seven natural capital attributes: leaf N content, water availability, litter/crop residue quality, mortality rate, sapwood amount, presence of a specific community/habitat type and abundance of a specific functional group. This suggests that these NC-ES linkages with timber production are only observed at local spatial scales, indicating that some NC-ES linkages with timber production have a strong spatial scale dependence, resulting in studies with coarser spatial scales underestimating the importance of some natural capital attributes for timber production. However, the user must also consider the effect of the differing sample size for these contexts. The majority (37) of studies evidencing NC-ES linkages for timber production have a local spatial scale and about a quarter (14) have a sub-national spatial scale. Very few studies had larger spatial scales.

Similarly, considering evidence from snapshot studies, which consist of nearly half of the studies (27), removes evidence for linkages between 14 natural capital attributes and timber production as shown by Fig. 4(b). One of these natural capital attributes is presence of a specific functional group, which lost evidence from all nine studies that supported a positive or negative linkage with timber production. This observation may be due to studies with shorter temporal scales missing longer-term ecological processes.

Finally, as shown by Fig. 4(c) filtering for evidence from European studies omitted a large proportion of studies (29) from North America and resulted in the removal of NC-ES linkages with 11 natural capital attributes, including species abundance and leaf N content, which lost evidence from five and seven studies, respectively. Furthermore, contrary to Fig. 4(a) and 4(b), under a European context there is very little evidence for NC-ES linkages with presence of a specific species type. This is due to the majority of European studies evidencing NC-ES linkages with timber production in the OpenNESS database focussing on natural forests rather than plantations (e.g. Vilà et al., 2013).

3.3. NC-ES linkages with other ecosystem services

Forests are known to generate multiple ecosystem services (Foley et al., 2007; Maes et al., 2012). Without holistic investigation of the NC-ES linkages, the forest manager may choose to promote a natural capital attribute that would have a positive effect on timber production but could lead to unintended consequences for another service they value. For example, the forest manager may receive payments from a water company to maintain good water supply, therefore they wish to avoid promoting natural capital attributes that will be detrimental to water supply. Furthermore, the forest manager is aware of payments for other ecosystem services their forest provides, such as atmospheric regulation and aesthetic landscapes, and therefore is interested in understanding the linkages between these ecosystem services and their natural capital attributes. The forest manager uses the LiNCAGES platform to explore the trade-offs and synergies between the unfiltered NC-ES linkages for

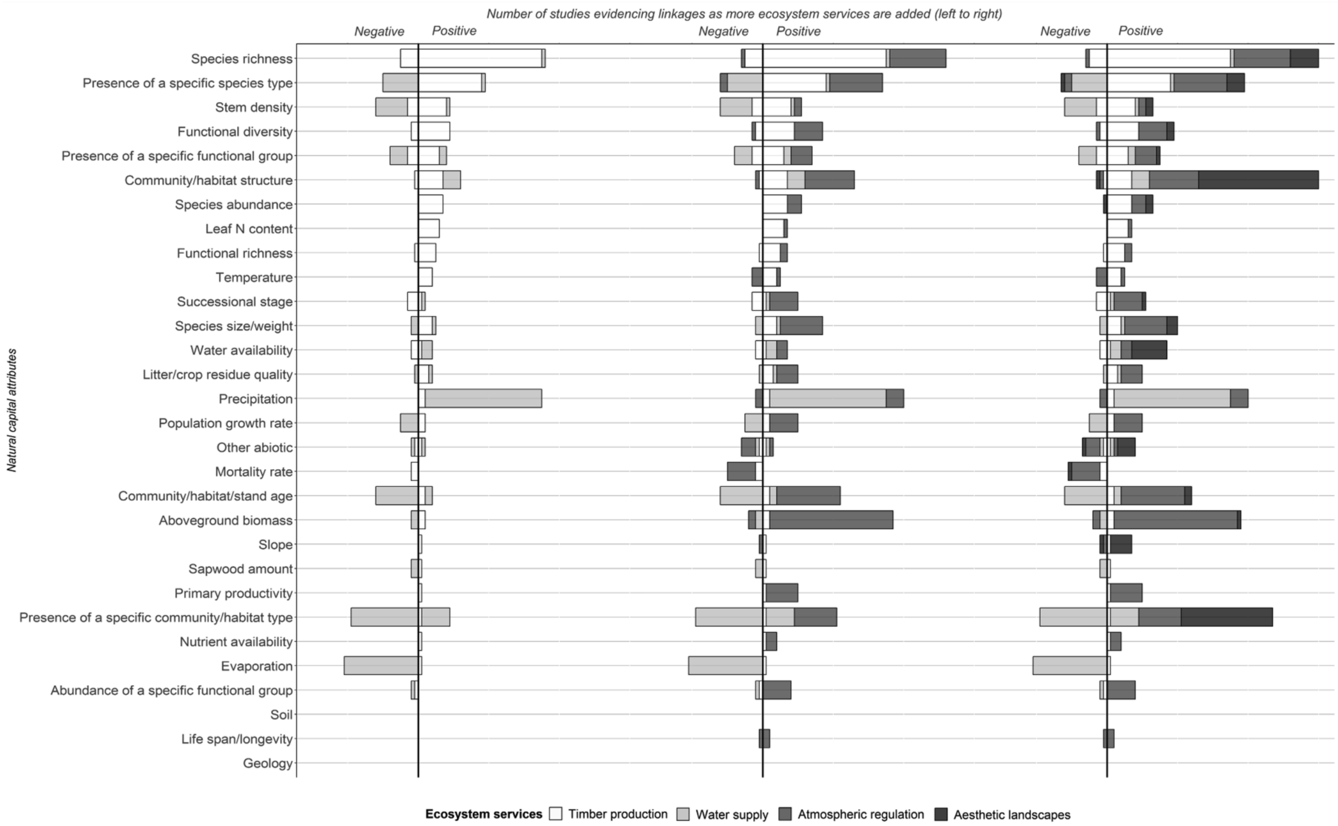

Fig. 5. Mirrored stacked bar graphs of the unfiltered positive and negative NC-ES linkages with the ecosystem services: timber production, water supply, atmospheric regulation and aesthetic landscapes. Left to right shows how the overall evidence for each of the NC-ES linkages changes as more ecosystem services are added. Evidence for positive and negative NC-ES linkages are shown on the positive (maximum = 60) and negative (maximum = 21) part of the x-axis respectively. *Natural capital attributes without evidence for linkages with timber production are not shown.*

timber production and three other ecosystem services: the provisioning service of water supply, the regulating service of atmospheric regulation and cultural service of aesthetic landscapes. Fig. 5 shows the amount of evidence for the positive and negative NC-ES linkages for the four services, and how the overall amount and direction of evidence changes as each ecosystem service is cumulatively added.

Fig. 5 shows many trade-offs between the ecosystem services, the majority being with water supply. Stem density and presence of a species type have positive linkages with timber production, yet also have negative linkages with water supply, so enhancing these natural capital attributes could support timber production but degrade water supply. Furthermore, Fig. 5 shows that community/habitat stand age leads to trade-offs between water supply and atmospheric regulation. For example, Webb and Kathuria (2012) found a strong inverse relationship between community/habitat stand age and catchment streamflow and Zhao et al. (2009) found that carbon storage increased with stand age in Chinese forests from 4 to 21 years. Fig. 5 also shows many synergies between timber production, atmospheric regulation and aesthetic landscapes, particularly for the natural capital attributes community/habitat structure, species richness and presence of a specific species type. Community habitat structure was particularly synergistic, changing from a natural capital attribute of mediocre importance to timber production to one of the most important natural capital attributes for multiple service provision of the four services the forest manager investigated.

However, many of the studies did not identify these synergies and trade-offs themselves. Only one study on timber production identified an interaction with water supply. Fifteen studies evidencing NC-ES linkages for atmospheric regulation identified an interaction with timber production, but only two for water supply. Studies evidencing NC-ES linkages for water supply identified 12 interactions with atmospheric regulation, and studies evidencing NC-ES linkages for aesthetic landscapes did not identify any interactions with any of the ecosystem services in Fig. 5.

3.4. NC-ES linkages for one natural capital attribute

The forest manager is interested in how they can better manage specific natural capital attributes to deliver multiple ecosystem services. They use the LiNCAGES platform to investigate the linkages between stem density and all the other ecosystem services available in the

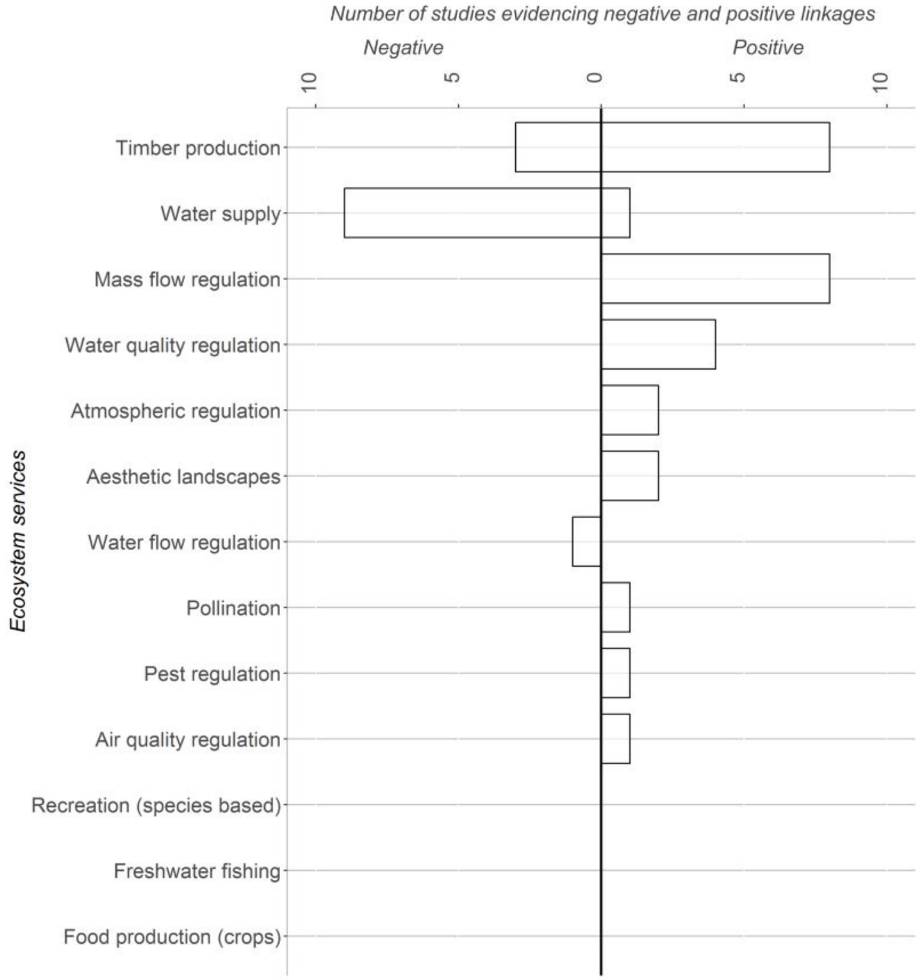

Fig. 6. Mirrored bar graph of positive and negative ES-NC linkages with the natural capital attribute of stem density. The amount of evidence for positive and negative ES-NC linkages is shown on the positive (right) and negative (left) part of the x-axis respectively.

platform, to assess the potential implications of changing stem density on the provision of these services. Fig. 6 shows the amount of evidence for positive and negative linkages between stem density and all 13 of the ecosystem services in the LiNCAGES platform.

Stem density has the most evidence for positive linkages with timber production and mass flow regulation as shown by Fig. 6. Higher stem density increases the productivity of forests (e.g. Amoroso and Turnblom, 2006) and reduces soil erosion (e.g. Lin et al., 2014). Stem density also has many negative linkages with water supply and water flow regulation as higher stem density results in significantly less soil water content (Kagawa et al., 2009; Zou et al., 2008).

3.5. Context dependency of ES-NC linkages for one natural capital attribute

The forest manager recalls the strong context dependency of NC-ES linkages with timber production (Fig. 4). Therefore, before deciding whether to promote stem density, they use the LiNCAGES platform to investigate the context dependency of these ES-NC linkages (Fig. 7).

Fig. 7(a) shows that under the context of spatial scales larger than local, evidence is lost for ES-NC linkages between stem density and the five regulating ecosystem services: mass flow regulation, water quality regulation, water flow regulation, pollination and pest regulation. This highlights the spatial scale dependency of ES-NC linkages, with regulating services most affected. Fig. 7(b) shows that snapshot spatial scale represents the unfiltered linkages well, only losing evidence for two ecosystem services (water flow regulation and pollination), which had very little evidence to begin with. The greatest context dependency of linkages with stem density comes from filtering for evidence from European studies. Fig. 7(c) shows that under this context, there is no evidence for the strong trade-off between stem density and water supply, and evidence for positive linkages with water quality

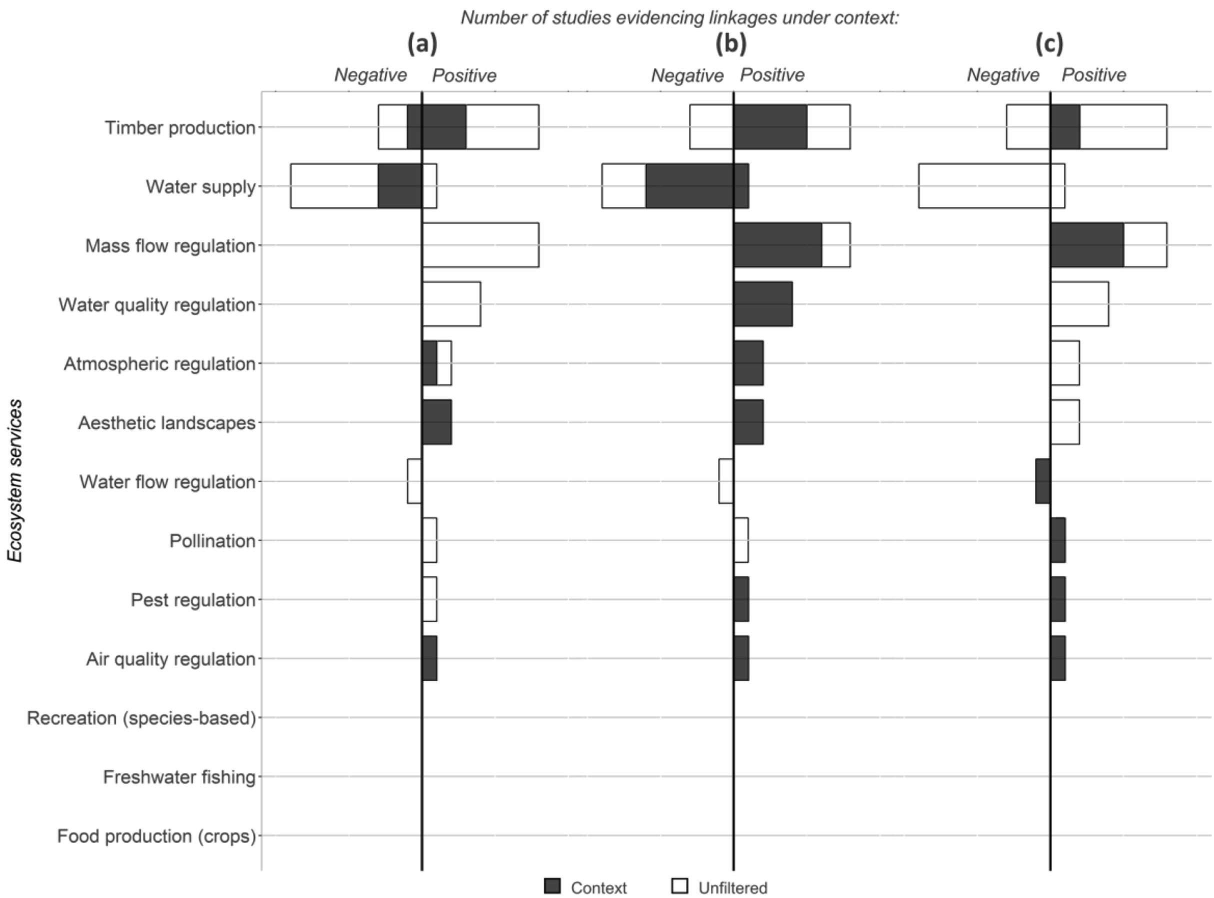

Fig. 7. Mirrored overlay bar graph showing the positive and negative ES-NC linkages with the natural capital attribute of stem density filtered for three different contexts: (a) evidence from studies with spatial scales larger than local, (b) evidence from studies with a snapshot temporal scale and (c) evidence from studies undertaken in Europe. Evidence for positive and negative ES-NC linkages is shown on the positive (maximum = 8) and negative (maximum = 9) part of the x-axis, respectively. For comparison, for each context the filtered ES-NC linkages (dark grey) are overlaid onto the unfiltered ES-NC linkages (white) from Fig. 6. See Fig. S6 for Figs. 6 and 7 as radar plots.

regulation, atmospheric regulation and aesthetic landscapes is lost. Furthermore, the amount of evidence for linkages with timber production is greatly reduced.

3.6. Applying multiple contexts through weighting

Using the knowledge gained throughout this process the forest manager can better decide on the weightings they will apply to the LiNCAGES platform to effectively deploy their context, while accounting for the context dependency of the NC-ES linkages. In this case, hierarchical weighting should be used rather than filtering, as the latter risks significantly reducing the sample size especially when using multiple study aspects simultaneously to apply context. See Supplementary Material Section 5 for a worked example using hierarchical weighting to investigate contexts (a), (b) and (c) simultaneously.

4. Discussion

4.1. Use case scenario

By applying the LiNCAGES platform to a hypothetical use case scenario, we illustrated the importance of context in understanding evidence about NC-ES linkages. Our hypothetical use case scenario journeyed through the decision-making process of a small-scale European forest manager using the LiNCAGES platform to explore the benefits, dependencies, synergies and trade-offs associated with the ecosystem service of timber production. The forest manager discovered which natural capital attributes have the most evidence for linkages with timber production, but also that the amount and direction of evidence for NC-ES linkages varies considerably with contexts such as spatial and temporal scale and study location. Other reviews also found strong context dependencies in NC-ES linkages in spatial scale (Cimon-Morin et al., 2013; Ricketts et al., 2016), temporal scale (Cimon-Morin et al., 2013) and location of study (Ricketts et al., 2016).

Our use case scenario has identified trade-offs and synergies that are missing in the literature. This evident lack of a holistic approach in the NC-ES studies reviewed in the OpenNESS database could lead to an underestimation of the value of multiple service provision (Balvanera et al., 2014). We also found these trade-offs and synergies to be context dependent. For example, at spatial scales larger than local, evidence is lost for linkages between stem density and five ecosystem services. This supports the findings of Duncan et al. (2015) who found that assessing NC-ES linkages at larger spatial scales misses key ecosystem functions that work at finer scales.

We demonstrated how multiple contexts can be applied simultaneously through the hierarchical weighting feature of the LiNCAGES platform (Supplementary Material Section 5). Weighting may be beneficial over filtering in such cases as it allows the user to give preference to certain contexts without filtering out potentially useful studies and considerably reducing the size of the evidence base. LiNCAGES gives responsibility for weighting to the user, allowing them to assign appropriate weights based on their expert knowledge and the specific purpose of their application. This is supported by the exploratory nature of the platform allowing users to quickly and transparently examine different weightings and to fully understand how each of their weighting choices contributes to the overall weight assigned to the study (Table S3). Nevertheless, the user should be cautious when interpreting the results of the weighted analysis; for this reason, LiNCAGES gives a clear indication of when weighting has been used, shown by the x-axis of Figs. S3 and S4.

Finally, we have demonstrated LiNCAGES using one use case scenario, focusing on one ecosystem service and investigating three context dependent aspects. There are 13 ecosystem services and a further 13 context dependent aspects (Supplementary Material Section 4) available to investigate within LiNCAGES. As such, LiNCAGES can be applied to a diverse range of scenarios, e.g., ranging from a national policy-maker interested in understanding the potential impact of nature-based solutions on ecosystem services to a protected area manager who wishes to better understand how protecting certain natural capital attributes might affect the delivery of ecosystem services. Due to the high context dependencies we identified in this use case scenario, we expect other use case scenarios to produce different results according to the needs of the user.

4.2. Comparison to other tools and platforms

Most existing tools and platforms for ecosystem service assessment consist of models supported by data input; these are usually GIS based and use remotely sensed data sources (Vorstius and Spray, 2015). To the best of our knowledge, we are not aware of an ecosystem service assessment platform that exclusively uses literature-based evidence for investigating NC-ES linkages. The most similar tool is MESER (Managing Ecosystem Services Evidence Review; https://meser.simomics.com) which provides a searchable literature review on how habitats can be managed to enhance their delivery of ecosystem services. Unlike LiNCAGES, MESER is habitat specific and does not account for other context dependent aspects of its underlying studies.

4.3. Limitations and further work

As with any literature-based synthesis, the evidence behind the LiNCAGES platform is likely to include reporting bias as non-significant or less interesting results are less likely to be published (Ricketts et al., 2016; Schwarz et al., 2017). This reporting bias could lead to an under-representation of the amount of unclear NC-ES linkages (Schwarz et al., 2017). Additionally, some natural capital attributes and ecosystem services are studied more than others (Adhikari and Hartemink, 2016; Balvanera et al., 2006; Hevia et al., 2017), leading to their potential over representation in the LiNCAGES platform. The OpenNESS database tried to overcome this by recording 60 articles per service (Pérez-Soba et al., 2017).

Due to this reporting bias, we ensured that the user can view the number of studies available under their current filtering and weighting choices. This means the LiNCAGES platform can also be used to investigate the reporting bias in the NC-ES linkage literature. For example, Fig. 2 showed that 12 of the natural capital attributes did not have evidence for NC-ES linkages with timber production and Fig. 6 showed no evidence for NC-ES linkages between stem density and three ecosystem services. Investigating whether these missing NC-ES linkages are legitimate or due to reporting bias can form important research questions to better direct research into NC-ES linkages. Furthermore, the LiNCAGES platform can identify the amount of studies in particular contexts, directing researchers to study contexts that are under-represented. For example, the LiNCAGES platform shows that very few studies with larger spatial scales than subnational provide evidence of NC-ES linkages with timber production. Similarly, the LiNCAGES platform can also investigate the reporting bias of the natural capital attributes. For example, Fig. 4b shows that linkages between species abundance and timber production are evidenced only by studies with snapshot temporal scale.

When using the LiNCAGES platform the user should be aware that only the amount of evidence for a linkage is displayed, as the OpenNESS database did not consider the statistical significance or effect size of linkages, due to the diverse nature of the evidence using many incompatible indicators and approaches (Smith et al., 2017). Additionally, judgement was involved in assessing the direction of the linkage (Smith et al., 2017). Furthermore, pooling evidence can sometimes oversimplify and mislead both scientific syntheses and management interventions (Martnez-Harms and Balvanera, 2012; Ricketts et al., 2016) as definitions of the context dependent aspects can vary between the studies (Englund et al., 2017). For example, Englund et al. (2017) found that studies in different countries have different definitions of spatial scale. For these reasons, the LiNCAGES platform should be used only as a guide, or as a starting point, to improve understanding of the main NC-ES linkages in the literature before the user explores specific aspects of the literature in further detail themselves. We have ensured that the LiNCAGES platform is as transparent as possible to aid with this literature exploration.

Currently the evidence behind the NC-ES linkages in the LiNCAGES platform is exclusively based on the OpenNESS database so the findings may be sensitive to the search terms and search engines used to identify the relevant papers (Ricketts et al., 2016). A list of all search terms used to create the OpenNESS database is given in Supplementary Material Section 2. To reduce this dependency and to ensure the longevity of the LiNCAGES platform we plan to add the functionality for other researchers to continue to add studies to the LiNCAGES platform in a consistent way to build up knowledge, ensuring that the evidence base can evolve.

5. Conclusion

This study follows the development of the novel LiNCAGES platform, and its application to a hypothetical use case scenario. We created LiNCAGES to provide a system for investigating evidence for NC-ES linkages that allows the user to account for the context dependent and sometimes non-holistic nature of this type of evidence. Through the use case scenario, we demonstrated the capabilities and need for the LiNCAGES platform.

Decision-makers in policy, practice and business are increasingly aware of the need to manage natural capital sustainably, but they lack suitable tools and evidence to enable them to assess the impact of different management decisions. In particular, there is a lack of understanding on how natural capital assets influence the capacity of ecosystems to supply different services in specific contexts. The LiNCAGES platform can be used by stakeholders to raise awareness and build understanding of important NC-ES linkages and trade-offs and synergies between service provision under their own context, thus providing scientific evidence that is more salient to their needs. It can also provide a resource for researchers to identify key gaps in this evidence base and to work collaboratively to target and collate additional evidence that can strengthen the foundations of sustainable environmental management.

The LiNCAGES platform can be accessed at: https://shiny-apps.ceh.ac.uk/LiNCAGES/.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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