Taking stock of the empirical evidence on the insurance value of ecosystems

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Abstract
Ecosystems can buffer against adverse events and, by so doing, reduce the costs of risk-bearing to society; benefits which have been termed 'insurance value'. Although the terminology is recent, the concept is older and has its roots in ecological resilience. However, a synthesis of studies through the lens of the insurance value concept is lacking. Here we fill this important knowledge gap by conducting a rapid evidence assessment on how, where and why the insurance value of ecosystems has been measured. The review highlighted the often substantial positive values that were associated with restoration, rehabilitation or avoidance of loss of natural ecosystems. However, many regions, ecosystems and hazards are not widely researched. Most studies focused on forests, agriculture and wetlands, often with an emphasis on habitat restoration to reduce flood risks. Over half the studies provided non-monetary or monetary estimates of value, reporting, for example, improved ecological function, achieved/achievable cost reductions or willingness-to-pay. Nevertheless, the evidence-base remains fragmentary and is characterised by inconsistent reporting of valuation methodologies. This precludes drawing general conclusions. We recommend that future studies of insurance value adopt a common approach to facilitate the development of a more robust evidence-base.

Keywords
Ecosystem services; insurance value; natural hazards; risk; resilience; rapid evidence assessment

Highlights

- We assess the existing empirical research on the insurance value of ecosystems;
- There is a mismatch between research topics and hazard types, location and severity;
- Values can be substantial, but there is little consistency in how they are calculated;
- We recommend a common approach to facilitate mainstreaming of insurance value.

Introduction

Globally, the frequency and severity of natural hazards is increasing (e.g. Royal Society, 2014), exposing a growing number of households, businesses, public authorities and infrastructure to multiple and new risks (e.g. Guha-Sapir et al., 2017; United Nations, 2016). This trend has been, and will continue to be, aggravated by climate change (IPCC, 2014), human population growth, demand for food and urbanisation, all of which can result in land use change, environmental degradation and biodiversity loss. Mitigating and adapting to new levels of risk will require novel ways to ensure that the positive aspects of ecosystems for human societies are integrated into decision and policy-making. One such possibility is to recognise how ecosystems can buffer against adverse events (Baumgartner, 2007) and thus reduce the costs of risk-bearing to individuals and wider society (Quaas and Baumgartner, 2008). This so-called 'insurance value' of ecosystems (Baumgartner, 2007) has emerged from the study of resilience, which is defined in the ecological literature as the capacity of a system to absorb shocks and reorganize itself to maintain its structure and functions, (Ehrlich and Becker, 1972). The term has been used to denote an ecosystem's ability to maintain function (and by extension the provision of ecosystem services to humans) under abrupt and gradual disturbances (Carpenter et al., 2001; Holling, 1973). As Baumgartner and Strunz (2014, p21) state "The economic relevance of ecosystem resilience is obvious as a system flip may entail huge welfare losses". Ecosystem resilience has, therefore, been recognised as an important ecosystem service (e.g. Maler, 2008; Maler and Li, 2010; Perrings, 1995).

However, insurance is not solely against catastrophic changes between system states. For people, reducing the severity, intensity and frequency of natural hazards is also of value, whether or not those hazards are associated with an abrupt system change. For example, maintaining a biodiverse and resilient forest ecosystem can provide 'natural protection' if it reduces the likelihood of a pest or disease outbreak within the forest itself and thus maintains the range of ecosystem services it provides. If the biodiverse, resilient forest is located upstream of an urban area, such services could reduce the adverse consequences of a flood, which could have considerable social value. This type of reasoning suggests close linkages between resilience, insurance value and sustainability (Brand, 2009).

Ecosystems can offer both protection, which can be defined as measures that reduce the likelihood of an adverse event, and insurance, which acts to reduce losses caused by an adverse event (Ehrlich and Becker, 1972). Baumgartner & Strunz (2014) refer to insurance value as the value of a specific function of resilience, namely the reduction of an ecosystem user's income risk from using ecosystem services under uncertainty. Thus, the insurance value of resilience is one additive component of total economic value (TEV) (Baumgartner and Strunz, 2014). Similarly, Pascual et al. (2015) consider 'natural insurance value' as a distinguishable component of the TEV of an ecosystem. Insurance value can then be further decomposed into self-protection (mitigation of risk) and self-insurance (adaptation to risk). The conceptualisation of insurance value, and the development and testing of solutions for measuring it, are, therefore, still being debated (Bartkowski, 2017; Baumgartner and Strunz, 2014; Mäler et al., 2007). Indeed, in studies reporting TEV it may not prove possible to disaggregate insurance value specifically. Therefore, while acknowledging its component parts, for the purposes of this review of existing empirical research, we use the term insurance value of ecosystems to refer to both insurance and protection components (Baumgartner and Strunz, 2014; Ehrlich and Becker, 1972; Pascual et al., 2015).

The economic conceptualisation of how we might value the protection and insurance contribution of ecosystems is rapidly evolving. However, there remains a gap between the theory of insurance value and the existing empirical research. Looking across the existing research base could reveal pointers as to how the concept could be mainstreamed and operationalised across a wide range of contexts. For instance, although the term 'insurance' is rarely used (but see The Nature Conservancy, 2018 for a recent example), the importance of insurance value of ecosystems is increasingly acknowledged in many related concepts. This is exemplified by a growing emphasis on "nature-based solutions" (NBS) in urban regeneration, flood risk management and other natural disaster risk reduction (Nesshover et al., 2017). Such NBS often provide co-benefits of which insurance value is just one (see Sukhdev et al., 2010). The International Union for Conservation of Nature (IUCN) also promotes NBS as an umbrella concept for a range of ecosystem-related approaches to address societal challenges (Cohen-Shacham et al., 2016). NBS, and related terms such as 'nature-based infrastructure', 'working with natural processes' and 'engineering with nature' (Nesshover et al., 2017) refer to interventions "which are inspired by, supported by or copied from nature" (European Commission, 2015, p. 4). An example of ecosystem-based approaches and NBS is natural flood management (NFM), which uses natural hydrological and morphological processes, features and characteristics to manage sources and pathways of flood waters (SAIFF, 2011) instead of hard-engineered flood defence infrastructure (Lane, 2017). Finally, ecological engineering has emerged as an approach to ecosystem restoration (e.g. Nesshover et al., 2017), for enhanced resilience of habitats and the communities that depend on them.

While the evidence base on ecosystem services and their values is growing (see e.g. Costanza et al., 2014), the focus thus far has been on provisioning and cultural ecosystem services. In contrast, insurance value is often related to regulating ecosystem services, such as the ability of biodiverse forest ecosystems to buffer risks from floods, fire, disease spread and other hazards. Despite the increasing interest in the buffering capacity of ecosystems and NBS to mitigate risks and to provide a range of other co-benefits, the evidence base on the ability of ecosystems to actually provide insurance value remains limited (e.g. Dadson et al., 2017).

Some caution is also needed when calculating monetary values for the extent to which ecosystems 'insure' against natural hazards. As climate and environmental changes continue, the resilience of ecosystems will be undermined, increasing the likelihood of systems tipping into new and unknown states. This has already happened in several cases (e.g. Rockstrom et al., 2009; Steffen et al., 2011), which suggests an emphasis on managing natural environments should be a priority to avoid hazards and regime shifts in the first place (e.g. Green et al., 2016). Regardless, the two are not incompatible, and the additional value of the insurance provided by well-functioning ecosystems could add to the strength of both monetary and non-monetary arguments for their preservation.

Acknowledging the difficulties of relying on past evidence to value the avoidance of unknown and complex shifts in system properties, it is nevertheless important to understand and quantify the current knowledge base. Interrogating the existing evidence on the quantification, qualification and valuation of the insurance value of ecosystem services across multiple contexts and ecosystems is a necessary starting point for mainstreaming and operationalising the concept. This could involve integrating an ecosystem's role in protection and insurance into insurance policies and developing new public and private insurance models for resilience.

To understand the current state of knowledge, we assessed the existing evidence on the insurance value of ecosystems, asking the following questions: (i) What existing empirical evidence exisits? (ii) Where has the research been carried out? (iii) How large are values associated with insurance as an ecosystem service, and how have they been measured? and, (iv) What lessons can we learn to ensure that future research allows us to more systematically 'value' the protection against, and avoidance of, natural hazards that ecosystems can provide? Although there is some literature explicitly discussing, or referring to, insurance value, it is relatively recent and limited. Therefore, we carried out a rapid evidence assessment using a suite of terms intended to capture the breadth of the existing relevant literature on valuing ecosystem services.

Methods

Rapid Evidence Assessment

To capture relevant knowledge from the existing literature, we undertook a configurative Rapid Evidence Assessment (REA). An REA is a constrained form of systematic review, which is limited to comprehensive database searches of the peer-reviewed literature and omits other forms of evidence gathering, such as manually searching the grey literature (Burton et al., 2007). REAs follow a transparent and reproducible procedure, decided on and articulated in advance, which minimises the chance of bias. The utility and value of REAs, and the evidence-based approach, is well established in the health, environmental and social policy sectors (Pullin and Stewart, 2006). Whereas classic quantitative aggregative reviews are likely to meta-analyse similar forms of data, configurative reviews seek to identify patterns provided by heterogeneity (Barnett-Page and Thomas, 2009). As such, they are ideal for synthesising evidence from different disciplines or methodologies.

REAs use published quantitative research data and centre on exploring frameworks, investigating complexity and placing research within its environmental and societal context (Greenhalgh et al., 2005). Through a detailed evaluation of existing conceptual, theoretical, modelling and empirical studies, an REA can explore whether the notion of insurance value of ecosystems offers novel ways to assess the value of natural environments for humanity. The objective of our REA was to synthesise findings from the existing literature on what value change in the quantity or quality of ecosystems has either in monetary or non-monetary terms that can be linked to any of the definitions of insurance value described above. Given that the notion of the insurance value of ecosystems is relatively recent, literature explicitly using the term has only emerged in the past decade. Nevertheless, the conceptual links between insurance value and resilience (e.g. Baumgartner and Strunz, 2014; Perrings, 1995), should mean that research which could underpin a better understanding of the quantification, qualification and valuation of the insurance value of ecosystems is likely to exist. To ensure that the review captured the breadth of existing studies, we developed a set of search terms to cover four main areas, namely: concepts of insurance and resilience, metrics of value, types of ecosystems and natural hazards (Table 1 and below).

Insurance, resilience, risks and ecosystem restoration

Search terms covered two of the main concepts of insurance value developed in the literature thus far, namely protection and insurance (Baumgartner and Strunz, 2014; Pascual et al., 2015). Given these concepts are directly related to resilience (Pascual et al., 2010) and the capacity of a system to remain at a given ecological state or avoid regime shifts (Walker and Meyers, 2004), search terms included 'resilience' and 'regime shift' in addition to 'insurance', 'protection' and their synonyms. A further concept of insurance relates to how ecosystems can internalise risk, and reduce the costs of risk-bearing to individuals and society (Quaas and Baumgartner, 2008). This argument has been developed around the idea that ecosystems provide insurance against the uncertain provision of ecosystem services in the same way that diversity in an asset portfolio does in financial markets investments (Baumgartner, 2007). Search terms also included various formulations of risk reduction, risk mitigation and risk management (

Table 1). Finally, given our specific interest in how ecosystems can be managed to prevent or reduce the occurrence and severity of risks and hazards, searches included terms such as ecosystem restoration and rehabilitation.

Metrics of value and valuation methods

A common approach to understanding the importance of ecosystems for human well-being is to assign monetary values to changes in ecosystems and the services they supply (e.g. Hanley and Barbier, 2009). This helps in making direct comparisons with other costs and benefits in decision-making processes (Kahneman and Sugden, 2005; Kumar, 2010). The notion of monetary value has been conceptualized in various ways; for instance, assigned values can be thought of as the measurement of a certain quality or level of importance (Schulz et al., 2017). This concept of value is rooted in neoclassical economics which considers humans as rational actors who seek to satisfy their preferences and maximise their personal utility through their choices (Dietz et al., 2005; Pearce and Turner, 1990). Accordingly, value is defined as "the change in human wellbeing arising from the provision of [an environmental] good or service" (Bateman et al., 2002; p1). These welfare changes can be compared by conducting monetary valuation studies that estimate people's willingness to trade-off scarce means (usually money) to achieve an environmental change, such as reduced flooding.

People's perceptions of nature's value, and shared or social values, often differ from standard economic models, and a broader range of values needs to be considered. Conventional economic valuation may not be appropriate for all facets of environmental goods such as non-use values (Nunes & van den Bergh 2001). Further aspects of ecosystem services are still more difficult to address, and the monetary amounts generated through an economic valuation framework may not capture the full value of ecosystems to beneficiaries (e.g. the role of intact ecosystems in maintaining system resilience; García-Llorente et al., 2011; Walker et al., 2008). For example, the Common International Classification of Ecosystem Services (CICES) identifies at least 11 groups of cultural ecosystem services (Haines-Young and Potschin, 2018), suggesting that a full account of the cultural value of ecosystems would require the consideration of them all (Dallimer et al., 2014). Understanding the multi-dimensionality of value increasingly requires the application of deliberative and participatory approaches (Kenter et al., 2015; Raymond et al., 2014). Our search terms reflected all these concepts, and are specifically intended to ensure that studies that have not valued benefits in monetary terms are included (Table 1).

Monetary and non-monetary measurement is one step in ensuring that values are recognised and, when appropriate, captured in decision making. Monetary values of ecosystems can be incorporated into decision-making through specific mechanisms such as incentives and price signals or via decision-making frameworks such as cost-benefit analysis or payments for ecosystem services (PES) schemes (Kumar, 2010; Martin-Ortega et al., 2019; Primmer et al., 2018). They have been criticised for converting nature into a tradable commodity, often associated with a process of privatisation (Gomez-Baggethun and Ruiz-Perez, 2011), thereby marginalising other frameworks for ecosystem conservation (Raymond et al., 2013). However, value capture does not have to lead to commodification (Hahn et al., 2015) or privatisation as property rights can be held collectively (Farley and Costanza, 2010), nor do schemes have to be driven by profit (Muniz and Cruz, 2015). In fact, public or self-provision of insurance value is a more likely scenario than market-like arrangements for the provision of insurance value (Paavola and Primmer, 2019). By exploring whether insurance values have subsequently been used to support instruments/tools/policies or other form of management arrangements we examined the extent to which measuring insurance value has thus far had an applied purpose, rather than being largely a result of scientific curiosity.

Ecosystems

An ecosystem is "a biological community of interacting organisms and their physical environment" (Millennium Ecosystem Assessment, 2005). In order to keep the review manageable, we focused on terrestrial and freshwater ecosystems and excluded coastal and marine ecosystems. Our search terms cover generic concepts (e.g. ecosystem, nature, environment, habitat, catchment), as well as specific habitats and land cover types (e.g. forest, city, grassland), taken from the IUCN definitions of terrestrial and freshwater habitats (IUCN, 2012). Previous reviews (e.g. Pascual et al., 2015; Perrings, 1995) and research (e.g. Chavas and Di Falco, 2012; Di Falco and Chavas, 2008; Isbell et al., 2015) have demonstrated the importance of biodiversity in ecosystem resilience, and its potential economic value. However, the focus of our review is on the impacts of ecosystem degradation/loss and rehabilitation/restoration, rather than associated changes in biodiversity. Our search terms, therefore, explicitly excluded biodiversity, its synonyms and mention of specific taxonomic groups.

Natural hazards

The framework was further bounded by a focus on natural hazards only. Geophysical and anthropogenic hazards were excluded with the exception of landslides and other mass movement events, as they are frequently managed through ecosystem-based approaches, such as the retention or restoration of forests. The list of search terms for hazard types was based on Guha-Sapir et al. (2017). Initial searches using generic terms for disease were refined based on a list of vector-borne diseases (WHO, 2017; Supplementary Material Table S1).

Table 1. Search terms used within the rapid evidence assessment of the insurance value of ecosystems. The list of vector-borne diseases is given in the supplementary material (Table S1). UK and US spelling variants, wildcards (*/?), common acronyms (e.g. WTP) and word stems were used in the database searches, but are not shown here for readability.

Insurance, resilience, risks and ecosystem restoration	Metrics of value and valuation methods	Ecosystems	Natural hazards
Risk	Value	Ecosystem	Flood
Hazard	Benefit	Nature	Erosion
Regime shift	Cost	Environment	Waterlog
Prevention	Price	Habitat	Inundation
Mitigation	Monetary	Catchment	Drought
Protection	Economic	Watershed	Avalanche
Reduction	Non-monetary	Forest	Fire
Avoidance	Willingness to pay	Savannah	Landslide

Defence	Willingness to accept	Shrub	Storm
Restoration		Grassland	Eutrophication
Management		Meadow	Vector-borne
Resilience		Tundra	Disease (see list Table S1)
Insurance		Wetland	Pest
		River	Extreme temperature
		Stream	
		Bog	
		Marsh	
		Swamp	
		Fen	
		Peatland	
		Lake	
		Desert	
		Arable	
		Pasture	
		Plantation	
		Farm	
		Agriculture	
		Urban	
		City	

The search process

Searches were carried out in July 2017, with no other time restrictions applied. Searches were conducted using Web of Science, which is one of the largest and most comprehensive publication databases covering both natural and social sciences, providing a powerful tool for identifying relevant literature. Search terms (Table 1) were actioned in two steps. We first conducted a joint search of "risk / hazard / regime shift & prevention / mitigation / protection / reduction / avoidance / defence / restoration / management" and then of "resilience / insurance". The results from the two searches were aggregated into a single library and duplicates were removed. Search queries yielded 10,371 results. To ascertain the relevance of individual studies, all papers were subjected to three sequential filters: i) examination of title; ii) examination of abstract; and iii) examination of full paper. After titles were checked for relevance, 1,171 papers were retained; this was reduced to 302 papers after reading the abstracts. After full papers were read, 154 were retained for data extraction (Supplementary Material Table S2).

Papers excluded at the full text stage consisted of studies: (i) of attributes that affect adoption of innovative practices, e.g. by farmers of biological control; (ii) solely of perceptions or attitudes to natural hazards and their management; (iii) on community involvement in disaster prevention; (iv) on technical engineered interventions; (v) of governance and procedures to reduce risk; (v) which estimated economic losses without discussing risk reduction; and (vi) those which only included notions of insurance value as part of their introductory context. An additional suite of papers had an ecological focus or only discussed environmental management, such as the expansion of vegetation, forest thinning, storm water drainage, societal impacts of hazards and spatial planning.

Data extraction and analysis

Due to the heterogeneity of the retained articles, in terms of research design, measures, and involvement of stakeholders or other participants, data were analysed using narrative synthesis. Its purpose was to identify the approaches that have been used to study concepts of the insurance value of ecosystems in the existing literature (Popay et al., 2006). Data were extracted covering four information categories: 1) study description; 2) insurance, hazards and ecosystems; 3) valuation, and; 4) wider context. In addition, vote counting was used to describe the frequency of specific approaches used to examine insurance value of ecosystems. While vote counting has deficiencies (e.g. giving equal weight to studies of different types, with different strengths of evidence, not accounting for publication biases), it is useful for preliminary interpretation of results across studies (Popay et al., 2006).

Study description

The study description included the year of publication and the year when the study took place; the type of study (whether it was a conceptual, theoretical, empirical or modelling work or a review); country/countries or global regions on which the research focused; and the specific location (as defined in the study itself).

Insurance, hazards and ecosystems

For each paper, we characterised how the notion of insurance was conceptualized, e.g. whether it referred to risk or hazard prevention, mitigation, avoidance or resilience. We also characterized the ecosystem and spatial scale (e.g. global, regional, national, or catchment) of the analyses, as described in the study itself. Information on the type of hazard was extracted and categorised based on Guha-Sapir et al. (2017), together with any further details, such as the frequency or timescale of the hazards. Hazards were classified into five broad categories: geophysical (for the purposes of this review, landslides and other mass movement events only), hydrological (flood, landslide, wave action), meteorological (storms, extreme temperature, fog), climatological (drought, lake outbursts, wildfire) and biological (animal accidents, epidemics, insect infestation).

We considered insurance with respect to ecosystem-based interventions or approaches. These included any changes in the ecosystem that result in a change in exposure to/protection from natural hazards or the mitigation of, or increase in, risk. Interventions that could mitigate a risk include, for example, the restoration or establishment of a habitat type and could include NBS and NFM (Dadson et al., 2017; Nesshover et al., 2017). In contrast, alterations to ecosystems such as habitat fragmentation, land-use conversion, river morphology alteration could result in increased exposure to hazards. We recorded the ecosystem services that these changes referred to (e.g. reduced water levels mitigating flood risk; soil loss abatement reducing erosion). Ecosystem services were classified using CICES (Haines-Young and Potschin, 2018) in order to identify which services are mentioned in the publication in relation to insurance value. CICES itself consists of three ‘sections’ of services (Regulating and Management, Provisioning, Cultural) which are further divided into 90 categories.

Undisturbed ecosystems offer in most, if not all, circumstances greater overall benefits than highly modified ecosystems (Balmford et al., 2002), albeit via a combination of a greater number of narrower benefit streams than ecosystems converted to intensive production (see also Turner et al., 2003). A similar argument for retaining and/or restoring ecosystem properties is central to global initiatives to achieve land degradation neutrality (Akhtar-Schuster et al., 2017) and mainstreaming the economic benefits of more sustainably managed agricultural lands into policy (ELD Initiative, 2015). We might expect that a similar rationale would apply to the role that ecosystems play in protection against, and avoidance of, natural hazards. We therefore categorised papers according to whether the alteration of ecosystems was an increase in extent/quality, a decrease in extent/quality, both or neither. Increases could include rehabilitation and restoration of habitats, enhanced vegetation complexity or improved diversity of habitats. Decreases could cover varieties of habitat loss, such as the conversion of natural habitats to agricultural production or urbanisation.

Valuation

We recorded whether studies associated changes in ecosystem service provision with a metric of value, even when the term 'value' was not explicitly used. We recorded if 'value' was expressed in non-monetary or monetary terms. When monetary values were reported, we recorded how the value was estimated (i.e. what type of valuation technique was employed), figures and units of those estimated values, as well as the year of the estimated values, and time scale of the value analysis (e.g. if the paper included an estimation of WTP for the delivery of ecosystem services over, for example, 30 years). We also noted whether values referred to marginal or total values. Studies differed as to whether they reported realized or anticipated values, where realised values were defined as those calculated as an estimation of the impact of an event that had already taken place (e.g. flood damage), and anticipated values as those calculated in anticipation of a future event (e.g. WTP to prevent future floods). Finally, we recorded whether the valuation exercises were associated with any policy instrument, such as a PES scheme, through which the value of the ecosystem, which is associated with insurance against natural hazards, could then be used to inform or underpin decision making.

Results and discussion

Study description and aims

The 154 articles retained for analysis were published between 1996 and 2017 (Figure 1) with the majority (86%, 133 papers) published after 2010. The growth of the literature manifests the uptake of the ecosystem service approach and the concepts that were popularised by the *Millennium Ecosystem Assessment* (Millennium Ecosystem Assessment, 2005). The largest number of studies was published in 2016, the last complete year in our review. Almost all of the retained articles were empirical (63 papers; 41%), or modelling (59 papers; 38%). The remainder were conceptual/theoretical (17 papers; 12%) or reviews (16 papers; 10%). Although the bulk (86%) of empirical and modelling articles was published after 2010, we could not ascertain whether earlier publication of theoretical work was driving a greater implementation of empirical studies. As expected because of our search parameters, the final set of articles did not include key theoretical outputs (e.g. Baumgartner and Strunz, 2014; Maler and Li, 2010), nor work on biodiversity underpinning ecological resilience (e.g. Isbell et al., 2015; Perrings, 1995).

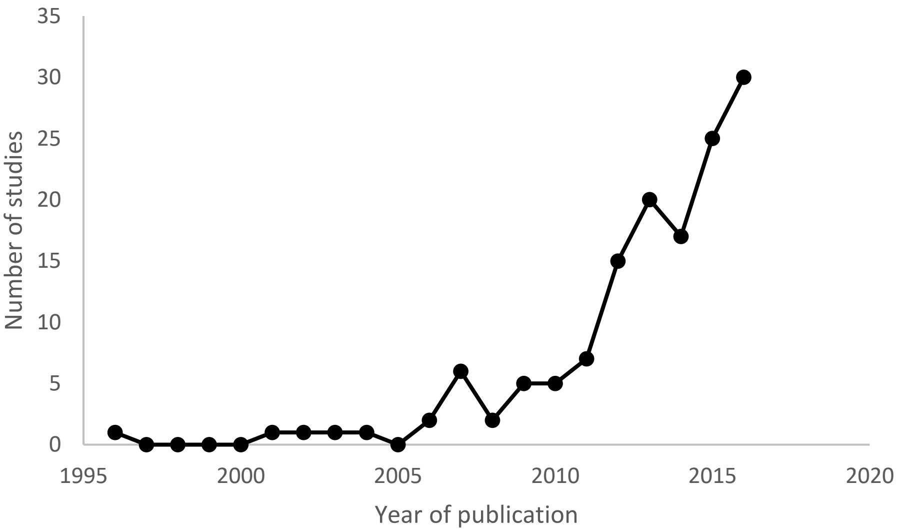

Figure 1. Number of studies addressing the insurance value of ecosystems published each year up to and including the final full year (2016) covered by the REA. A further 14 studies that were included in the review process, were published in 2017 prior to the search cut-off date (July 2017).

A wide range of aims were pursued in the reviewed studies, but the largest proportion (41%) investigated the effect of interventions to mitigate risk or to address environmental degradation. Common interventions were ecosystem restoration, reforestation and changes in land management practices. The second most common aim (17%) was the assessment of alterations to the ecological quality of the ecosystems, such as the diversity of forest cover, or the structure of riverbanks or wetlands. About a half of these included the value of ecosystem services. The role of forests, and forest cover, was a particularly common subject, as were the effects of altering river morphology, and the restoration or loss of wetlands. Approximately 6% of studies provided novel frameworks, conceptualizations or methodological approaches to address or integrate some of the above aspects of insurance value (e.g. effects of interventions and environmental conditions), often with the aim of supporting improved ecosystem or landscape management.

Insurance, hazards and ecosystems

Of the retained studies, 24 had a global focus (Figure 2). In the global studies, hydrological and climatological hazards were most often examined through empirical analyses (e.g. Bradshaw et al., 2007; Shreve and Kelman, 2014) or conceptual models (e.g. Kiedrzynska et al., 2015). More studies focus on regions in the Global North than on the Global South. Western Asia (2), South Asia (2), South-eastern Asia (5) and Eastern Europe and Central Asia (3) were relatively understudied. This is concerning because these regions experience the greatest proportion of natural disasters (Guha-Sapir et al., 2017).

The majority of studies in North America and Africa focused on climatological disasters, whereas hydrological disasters were the focus of studies on Europe, Eastern Asia, South-eastern Asia and Oceania. For Africa, this reflects not so much the number of events (there are more hydrological than climatological events) but the fact that climatological disasters kill and affect more people than do hydrological events (Guha-Sapir et al., 2017). For North America, the inconsistency between the focus of studies and the type of disaster is greater. Meteorological disasters are the most frequent and costly; yet climatological disasters were studied more often. A similar pattern was found in other regions.

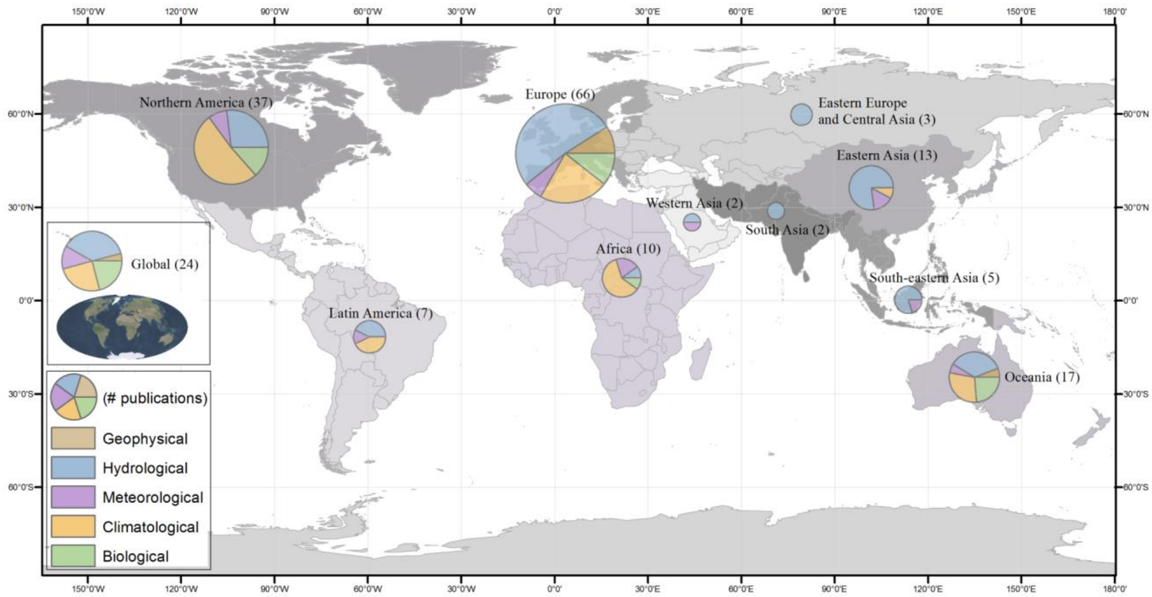

Figure 2. Number of studies per hazard type across 10 global regions and for global studies (inset). Circle size indicates the number of studies and the breakdown indicates the relative frequency of the five hazard types. Hazards were classified into five broad categories (Guha-Sapir et al., 2017): geophysical (earthquake, mass movement, volcanic activity), hydrological (flood, landslide, wave action), meteorological (storms, extreme temperature, fog), climatological (drought, lake outbursts, wildfire) and biological (animal accidents, epidemics, insect infestation).

The majority of studies focused on forests, agricultural lands and wetlands/floodplains (**Error! Reference source not found.**), with an emphasis on how habitats can reduce flood hazards associated with rainfall events. For example, forests can mitigate floods because they act as a "sponge" and slow down the flow of water (e.g. Dymond et al., 2012). The peri-urban and urban studies were often on fire management in natural or semi-natural vegetation systems. For example, Miller et al. (2017) examined a bond-financed wildfire risk mitigation partnership, which focused on watershed forest management to prevent flood damage and to protect water supplies from impacts of large-scale and/or severe wildfires.

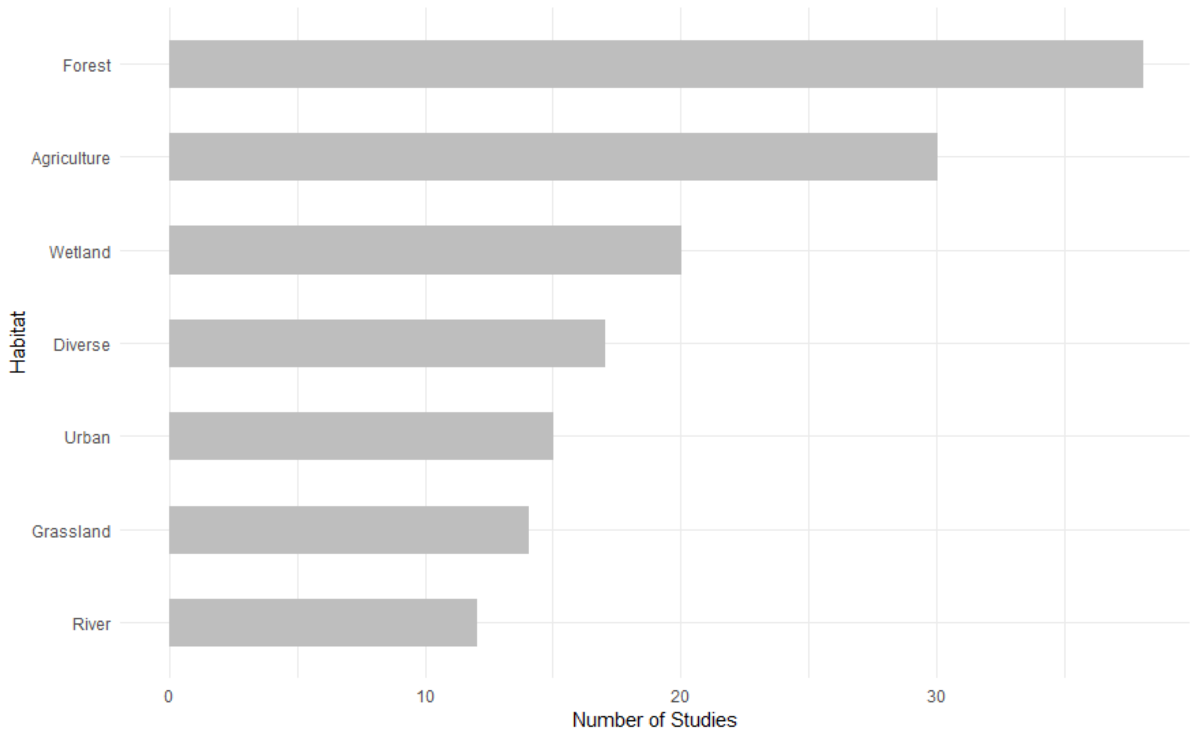

Figure 3. The number of studies in which a specific habitat or land cover is mentioned. Ten studies did not indicate a habitat type. Studies that referred to more than one habitat (e.g. a forest/agriculture matrix) are included in the "Diverse ecosystems" category.

Watersheds or catchments were the most common spatial scale of research (47 studies; 31%), reflecting the large number of studies focusing on water management and floods. Other scales included forests (12 studies, 8%), urban areas (16 studies; 10%) or even single hazard events. Across the reviewed papers, spatial scales tended to reflect relevant governance units, be that local (Miguez et al., 2015), regional (Holecy and Hanewinkel, 2006) or national (Felton et al., 2016), even though the management of many ecosystems is carried out by private landowners. However, 39 studies did not provide data on the examined spatial scales, limiting our ability to assess the financial implications of the threat or the mitigation provided from ecosystem services.

Study timescales also varied. Fourteen studies provided evidence about the frequency of events (flood or fire) whereas 31 studies looked at a single growing season or year. Seven studies analysed historical data to estimate the benefits of ecosystem services, whereas the largest number of studies (22) took a forecasting approach, spanning periods of years to tens of years. The forecasts varied in their determination of the frequency of events in the future, with some (19) taking into account specific climate change predictions, whereas others (3) used the historical frequency of events in their extrapolations.

Around 80% (124) of the papers referred to more than one ecosystem service, with a total of 243 different ecosystem services mentioned across studies. Of these, six were cultural and 16 provisioning services. However, the majority (221; 220 biotic and one abiotic) were regulatory and maintenance services. Sixteen of the 22 CICES sub-categories of the regulation & maintenance services were covered in the papers included in the review. Over a third of studies (36%) were about "Regulating the flows of water in our environment", 12% about "Controlling or preventing soil loss", 10% about "Protecting people from fire" and 8% about "Controlling pests and invasive species" (e.g. Cai et al., 2011; Cross et al., 2015; Jones et al., 2016; Miller et al., 2017 respectively) (Figure 4). A further group of studies examined improved ecosystem resilience more generally (e.g. Holman et al., 2011; Li et al., 2015), indicating potential gains across a wider set of hazards; an approach which might be particularly appealing for policymakers.

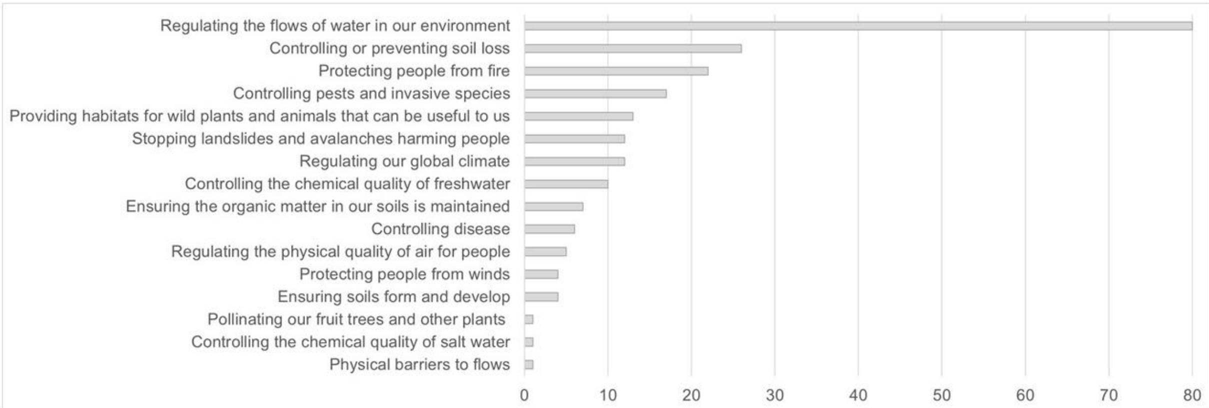

Figure 4. Classification of the insurance value of CICES regulation & maintenance ecosystem services in the reviewed studies. (Supplementary Material Table S3).

Over two thirds of the studies (106, 68%) examined the insurance concepts associated with an increase in extent/quality of an ecosystem, 21 studies (14%) looked at insurance in the context of a decrease in extent/quality, and 18 studies (12%) involved changes to both directions: e.g. the loss and restoration of mangroves (Everard et al., 2014). The remaining studies did not specify, or were not explicitly concerned with, changes *per se*. Increases in extent/quality included: (i) reforestation (Galve et al., 2015); (ii) urban green infrastructure interventions (Connop et al., 2016); (iii) NFM, such as wetland construction and restoration (Babbar-Sebens et al., 2013); (iv) increased vegetation complexity (e.g. retaining ground cover in orchards to enhance populations of natural enemies of pests (Colloff et al., 2013)); (v) sustainable land management practices (e.g. Speranza, 2013); and, (vi) more diverse systems (Newton et al., 2012; Schlapfer et al., 2002). In all cases, papers studying increases of these types hypothesised that changes would lead to an increase in protection from, or avoidance of a natural hazard. Conversely, decreases in extent/quality of ecosystems were associated with increased actual or perceived risks of exposure to natural hazards. Decreases in extent/quality included: (i) the conversion of natural habitats for production purposes (e.g. the conversion of natural forest to a rubber plantation (De Graff et al., 2012)); (ii) urbanisation (Brandolini et al., 2012); and, (iii) the loss of natural habitats such as forests (Brang, 2001) and wetlands (Brody et al., 2007).

Only 24 studies (15%) explicitly related changes in ecosystem properties and service provision to an insurance value. Although specific references to insurance value were rare, the most common related concepts included the reduction of a risk or hazard (59 papers; 38%), its mitigation (44 papers; 28%) or how an ecosystem provides resilience against risks or hazards (41 papers; 26%;

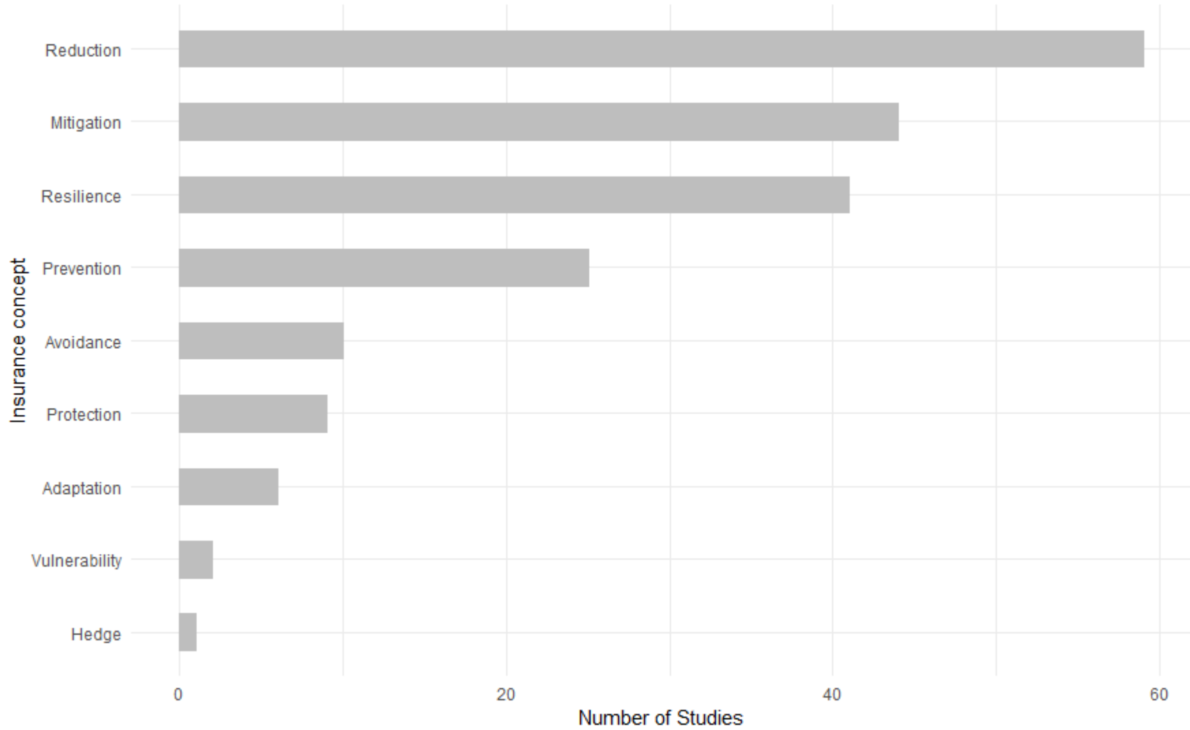

Figure 5). Studies examining how risks were reduced following changes in ecosystems included estimating the WTP of downstream agricultural water users for forest restoration to reduce wildfire risk (Mueller et al., 2013), and modelling how alterations in agricultural land use could reduce flood risk in large catchments (Schilling et al., 2014). The deterioration in ecosystem resilience as result of vegetation losses was investigated in drylands using a spatially explicit model (Mayor et al., 2013). Brown et al. (2012) examined the importance of mitigating flood risk in a conceptual paper on building urban resilience against climate change. Another study explored whether ecosystem properties could provide a hedge against future uncertainty (Boughton and Pike, 2013). It conceptualised insurance as the hedging role that floodplain restoration plays against climatic uncertainty (storm size, frequency, intensity). Rehabilitation expanded the opportunity fish had to migrate by 16-28%, and lessened the risk to fish migration of fewer, larger storms. Barbedo et al. (2014) modelled the effects of river restoration on flow rates around the city of Paraty, Brazil, in order that the benefits of river restoration could be considered in decision-making. However, overall Few studies were linked to decision-making, indicating an opportunity to better mainstream insurance values in ecosystem restoration.

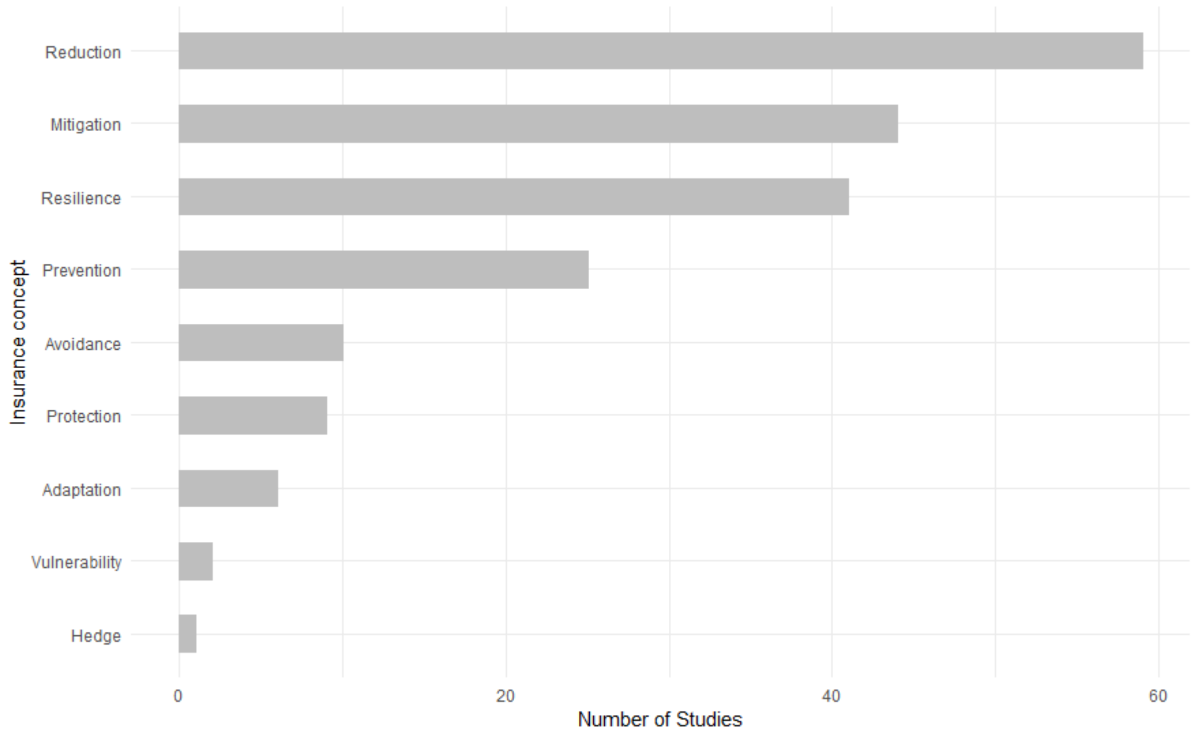

Figure 5. Number of reviewed studies using different concepts of insurance value of ecosystems.

Valuation

In total, 88 studies referred to some notion of value: 55 mentioned at least one monetary value and 18 a non-monetary value (in dark and light grey respectively;

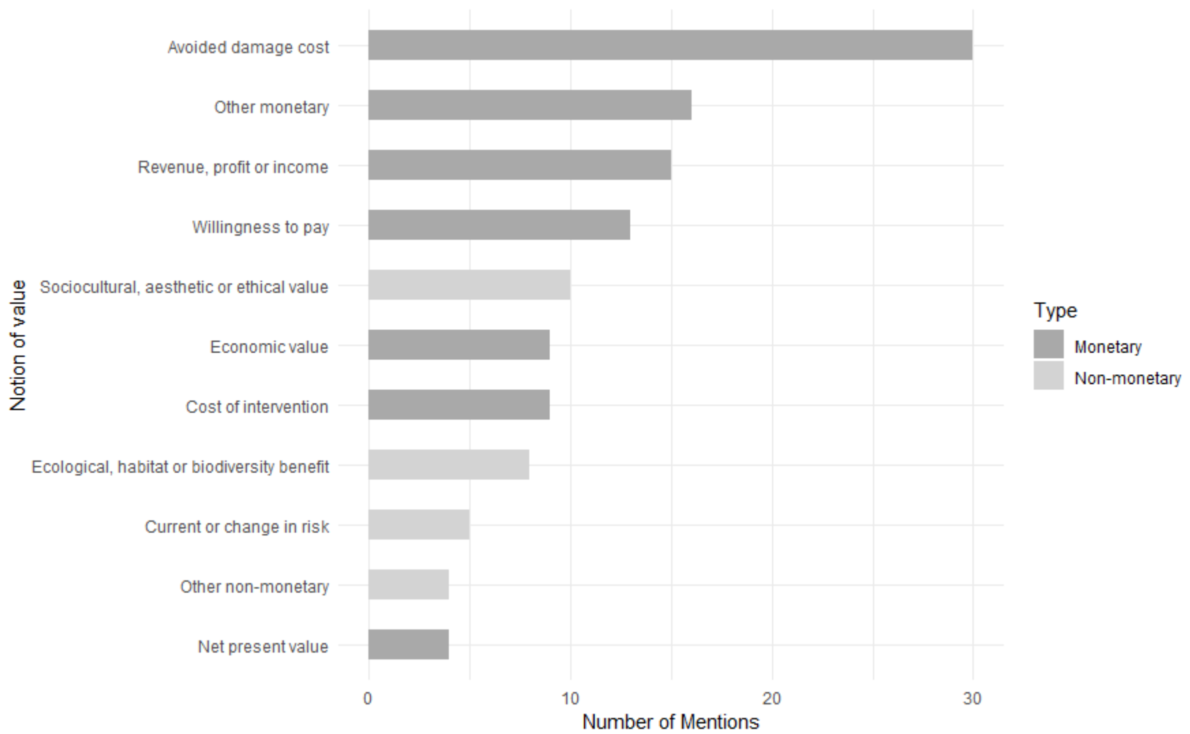

Figure 6), and 10 both types of value. Studies that referred to non-monetary values assessed sociocultural, aesthetic or ethical values (10 papers), ecological, habitat or biodiversity benefits (8 papers), or other non-monetary values (4 papers). Non-monetary valuation represented a modest proportion (17.9% of the reviewed papers) of the research carried out thus far. This perhaps reflects the relatively recent understanding of the importance of incorporating the multi-dimensionality of value in assessments of ecosystem services (Kenter et al., 2015). It further illustrates the need for more research to ensure that, among other aspects, altruistic, shared, social and socio-cultural facets of the insurance values of ecosystems are investigated (Kenter et al., 2015; Raymond et al., 2014; Schmidt et al., 2017).

Baumgartner & Strunz (2014) refer to insurance value as the value of a specific function of resilience, which reduces an ecosystem user's income risk associated with using ecosystem services under uncertainty. In contrast, Mäler and Li (2010) estimate a broader shadow price for resilience. It was not possible to separate out these theoretical concepts of 'insurance value' in the reviewed articles; this is unsurprising given the relatively recent emergence of the concepts in the literature. Nor, as expected, was it possible to separate out values specifically for insurance from calculations of TEV made in the papers (cf. Pascual et al 2015).

Monetary valuation studies used avoided damage cost, revenue or WTP approaches. TEV, marginal values and various use and non-use values were all estimated by these means. Ten studies did not specify which value was used. When monetary values were estimated, numerous different methods were applied. The most common were avoided cost or damage cost methods (e.g. using parcel level analysis, production function to estimate the expenditure needed to mitigate or compensate for the negative effects of a change in the environment), replacement cost method (e.g. assuming that the costs of replacing or repairing a deteriorated environmental service provides a reasonable estimate of its value (Logar and van den Bergh, 2013), such as replanting a forest or resettling people), choice experiments and contingent valuation (

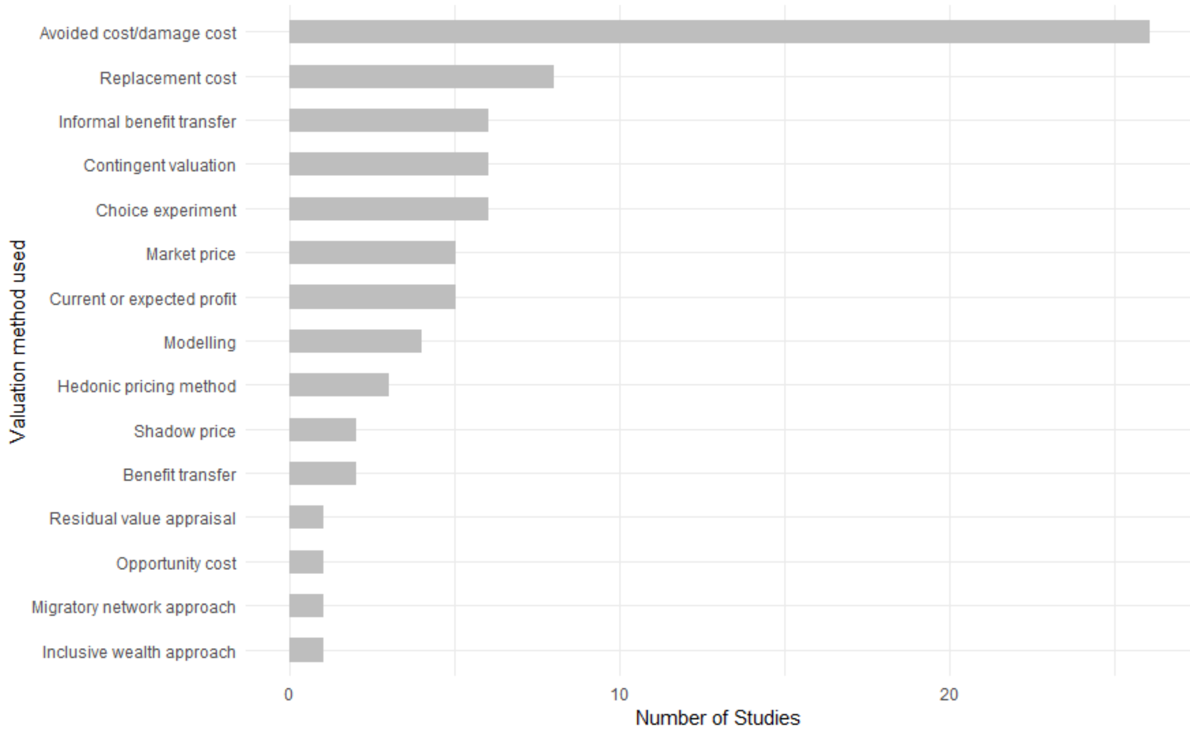

Figure 7).

Option and quasi-option values were not explicitly considered in any of the papers, despite the relationship between insurance and option values (i.e. the value of having the option of future use of an ecosystem service). An option value is, therefore, an insurance premium or the value of waiting for the resolution of uncertainty. Although difficult to quantify, quasi-option values, or the welfare gain associated with delaying decisions when there is uncertainty about the costs or benefits of a given course of action, may also constitute a significant portion of the value of retaining resilient ecosystems, in the face of increasing uncertainty driven by environmental or climate change.

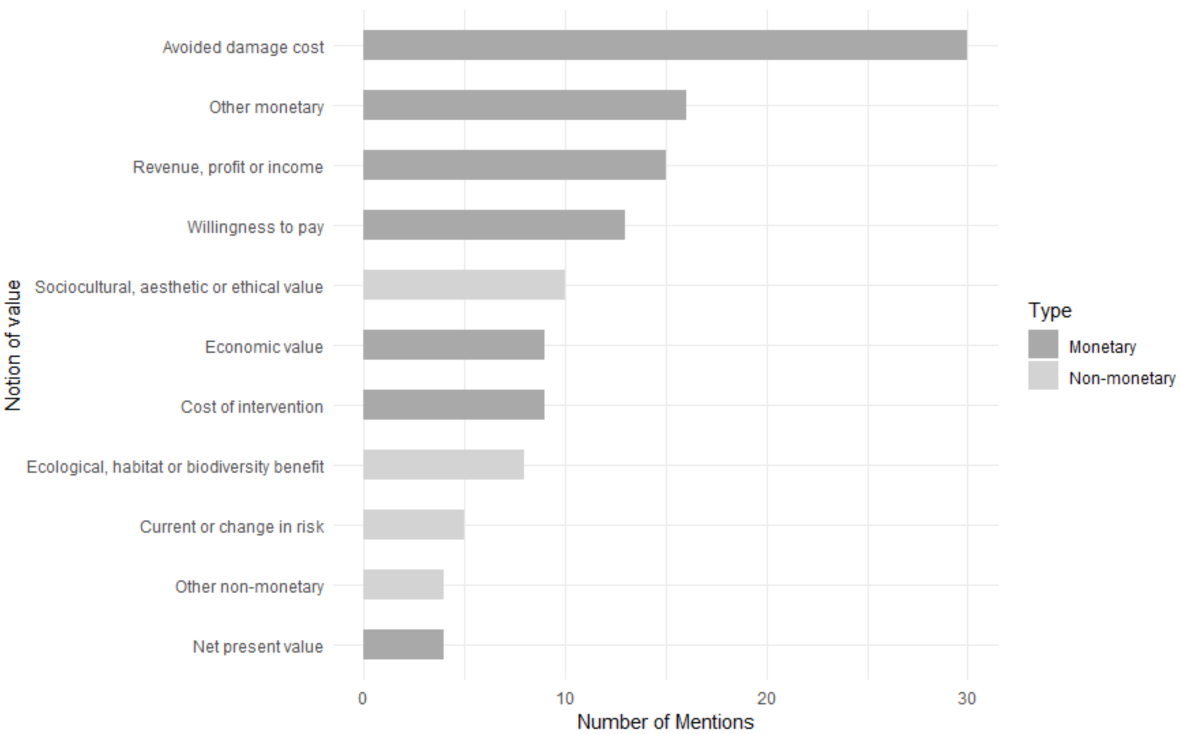

Figure 6. Number of times each notion of value (monetary in dark grey, non-monetary in light grey) was used in the reviewed studies.

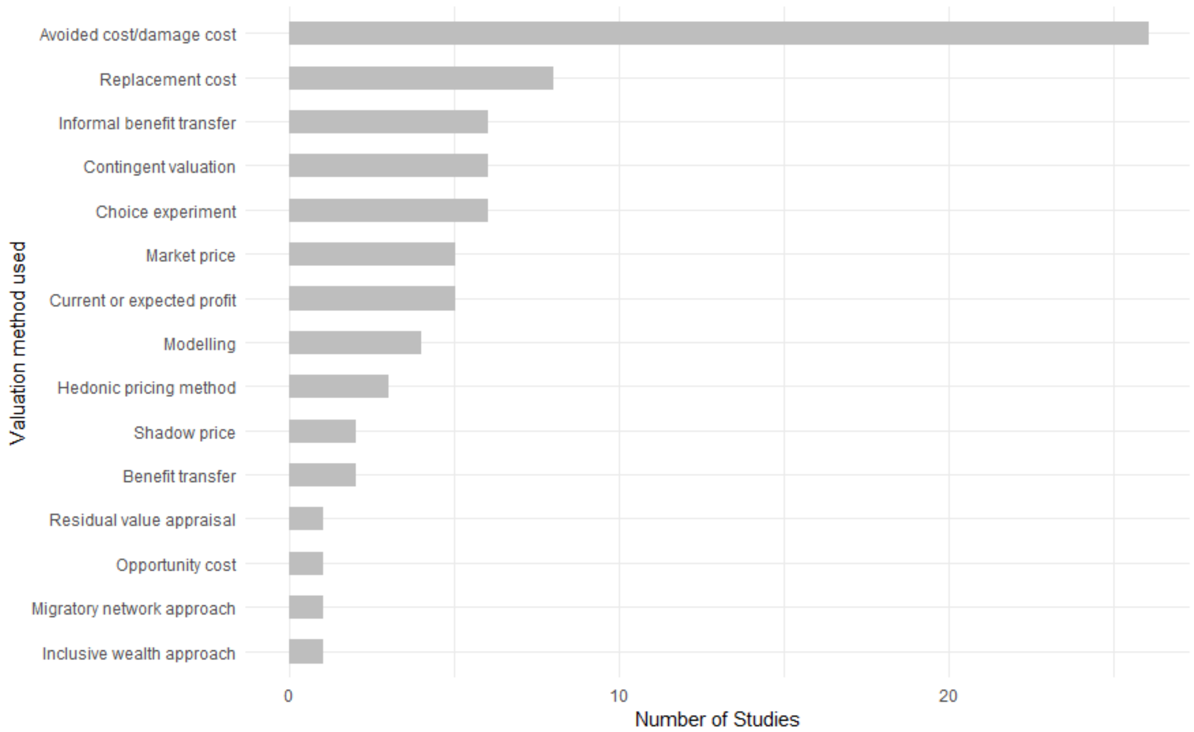

Figure 7. Valuation methods used to assess the monetary value of insurance services provided by ecosystems.

Direct comparison of values between studies was difficult as they varied in the theme, spatial and temporal scale, the consideration of scenarios, units reported, year the study was carried out and the monetary amounts associated with the insurance service. For instance, Kousky and Walls (2014) reported avoided flood losses of over $110 million (all values here in 2017 USD to facilitate comparison) for a 100-year event in a floodplain in Missouri, while Brody et al. (2007) reported $149.6 million over a 5-year period for 383 floods across counties in Florida. Similarly, two contingent valuation studies found a mean WTP of $5.22 per month, per household for hazard protection from wildfires, drought and floods in Arizona (Mueller, 2014), and a mean WTP of $28.87 - 48.61 per person, per year across seven scenarios for flood risk reduction in a river basin of Japan (Zhai et al., 2006). The fire prevention WTP values range from $87.83 per person, per year to $509 per hectare, per year. Avoided flood losses ranged from $0.02 to $58.2 per household, per year, or avoided flood damage costs from $21.76 to $21,158 per hectare, per year. Even studies of similar hazards, using similar techniques, provide radically different estimates of value. This could be for a variety of reasons, not least because disaggregating insurance value from TEV is not straightforward (Pascual et al 2015).

The lack of consensus on the minimum criteria for assessing costs and benefits associated with disaster risk reduction (Shreve and Kelman, 2014) was reflected across the studies. For instance, while defining time horizons is essential in cost-benefit analyses (CBA), only thirty studies mentioned a time scale for the values generated, and these ranged from one to 115 years (median 6 years). There were 35 prospective studies on anticipated values and 11 retrospective studies estimating realised values of past events. Eight studies estimated both realised and anticipated values. Long-time scales may be particularly important when considering climate change, but do not necessarily overlap with relevant policy and decision making timescales. Bringing in other perspectives on value, and a consideration of long-term environmental and climate change and vulnerability processes (Feuillette et al., 2016; Shreve and Kelman, 2014), may require greater use of participatory decision making and valuation tools, such as Multi-criteria analysis (MCA) (Shreve and Kelman, 2014).

Scale was an important concept in the reviewed studies, for instance as an argument for managing entire ecosystems to buffer against hazards (Berger and Rey, 2004). Studies largely reflected the scale of the ecosystems in question (e.g. catchments, particular high elevation ecosystems Mariotte et al., 2013) or scales at which relevant policies might operate (e.g. regional European Union adaption strategy (Holstead et al., 2017). Taking the latter approach is a pre-requisite for research to inform decision and policy making (Dallimer and Strange, 2015), and might be one reason why so few papers make the link between the values that they calculated and how these values might be used to influence decisions about land use and management. Value capture models were mentioned in 21 of the studies that estimated a monetary value. PES schemes were mentioned most frequently, followed by management plans and decision support tools, such as CBA or MCA (

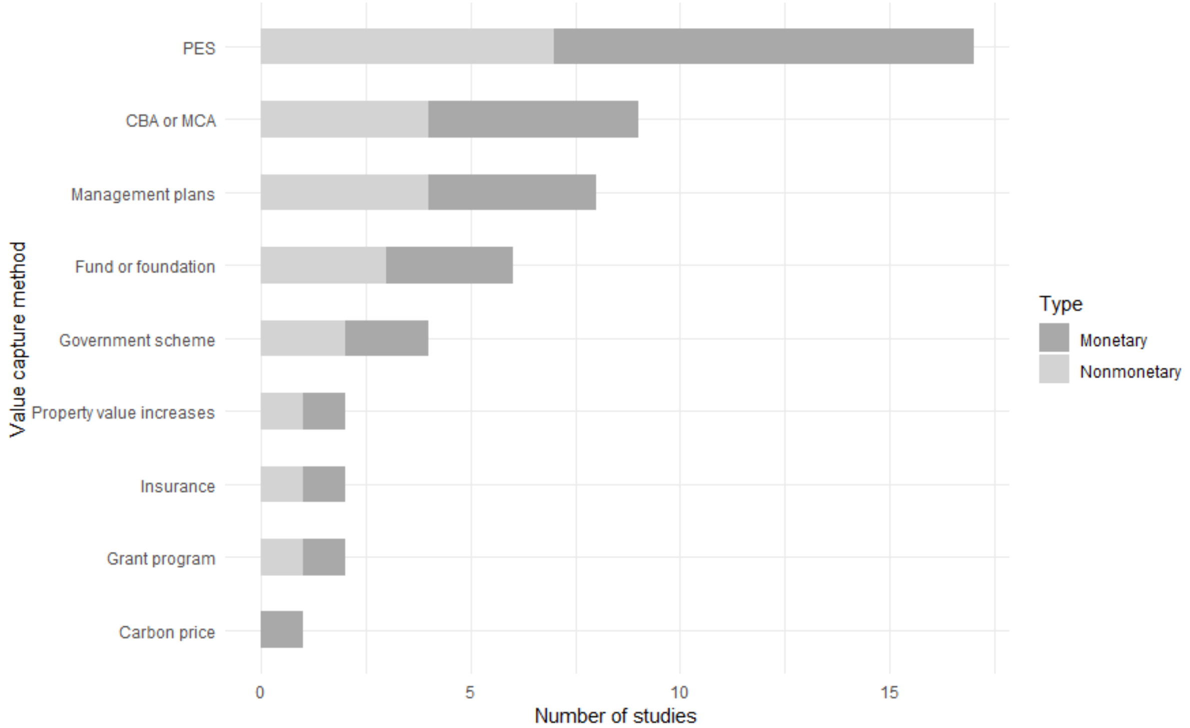

Figure 8). Innovative value capture models such as microfinance, crowdfunding and insurance trusts were not discussed (e.g. Abraham and Fonta, 2018; Beck et al., 2018; Dey et al., 2019; Gallo-Cajiao et al., 2018).

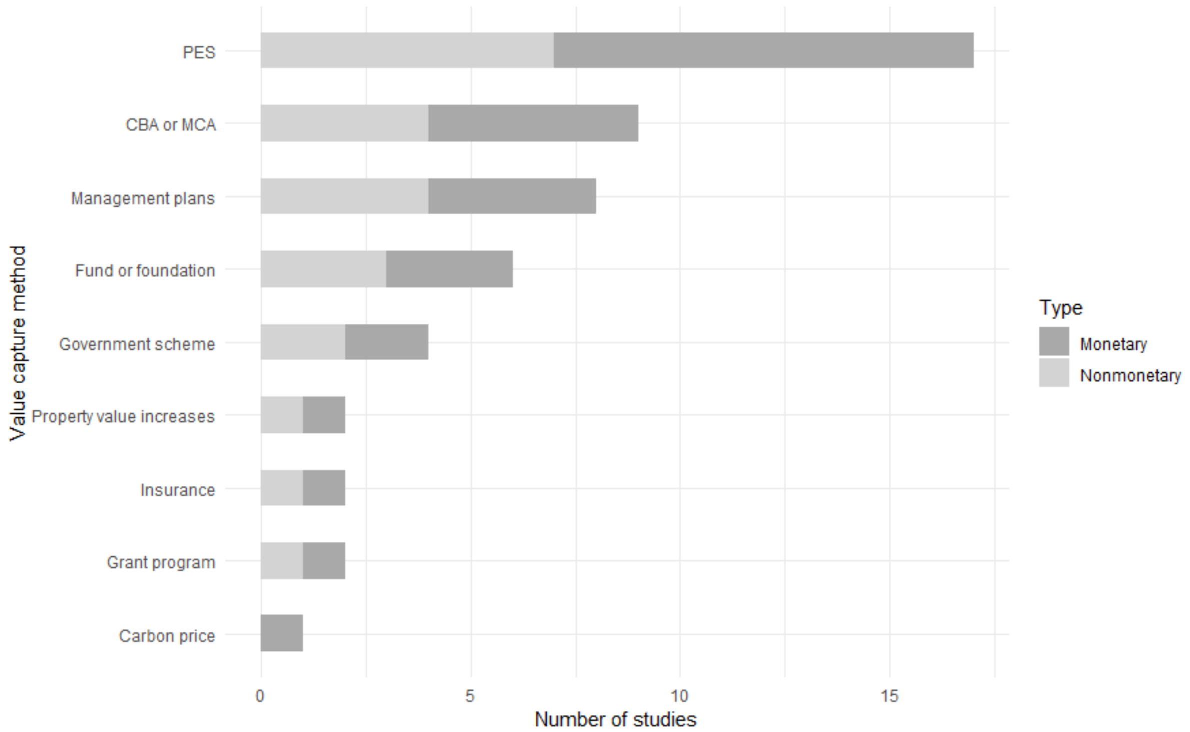

Figure 8. Number of reviewed studies (monetary in dark grey, non-monetary in light grey) distributed according to the value capture model(s) mentioned (n=21). CBA = cost-benefit analysis; MCA = multi-criteria analysis; PES = payment for ecosystem services.

Climate change and co-benefits

The frequency and intensity of natural hazards, as well as the number of people vulnerable to suffering losses, is predicted to increase with climate change (Royal Society, 2014). Despite this, climate change was an integral concern in only about a third of the reviewed studies (57 of the 154); for example, as a driver of biodiversity loss, or increased flood and desertification risk (Kelt and Meserve, 2016; Kiedrzynska et al., 2015; Kulakowski et al., 2017; Oliver et al., 2015). There were also references to climate change mitigation through, for example, peatland carbon sequestration and soil management, and to adaptation using green urban infrastructure (Connop et al., 2016; Gilbert, 2013; Holman et al., 2011). A few studies discussed the insurance value of ecosystems as part of a strategy for climate change adaptation. For example, forest restoration could help reverse biodiversity loss, pest outbreaks, and human disease, thereby addressing cascading risks (Morlando et al., 2012), or resilience could be increased in a particular biome such as forests (Chapin et al., 2007; Colloff et al., 2016). Adaptation planning is also referred to in some studies (Koschke et al., 2013) in relation to specific circumstances such as agroforestry, reforestation (Lasco et al., 2014; Locatelli et al., 2015), and floodplain management (Kiedrzynska et al., 2015).

Co-benefits (or the assessment of multiple benefits from ecosystems) are often used as an argument in favour of ecosystem-based approaches over hard-engineering infrastructure (Raymond et al., 2017). Co-benefits were referred to in 95 (62%) papers. In common with the wider literature, papers that did assess co-benefits noted that they can often dwarf the target benefit, e.g. water quality benefits from improved flood control (Brouwer et al., 2016; Dumenu, 2013; Richert et al., 2011). The potential for mitigating several risks simultaneously or for generating cascading benefits was a recurring theme (Felton et al., 2016; Morlando et al., 2012). Co-benefits were most commonly described as socio-economic (rather than environmental) benefits, such as the protection of public infrastructure, public health and avoided costs from fire suppression or disruption (Huang et al., 2013; Kelly et al., 2015; Miguez et al., 2015).

Conclusions

The rapid development of initiatives such as NBS, NFM, integrated pest management and ecological engineering exemplify how ecosystems can provide a form of 'natural insurance' by enhancing socio-ecological resilience. Ecosystems can buffer against adverse events and gradual losses such as flooding and soil erosion, thereby reducing the costs of risk-bearing for individuals and wider society. These benefits have been conceptualized as the 'insurance value' of ecosystems. We conducted an REA across a heterogeneous body of literature to take stock of the existing empirical evidence on how, where and why the insurance value of ecosystems has been measured. REAs have the benefit of being transparent and repeatable, in terms of search terms used and data extracted. Although our framework had limitations (e.g. the explicit exclusion of biodiversity and related terms), following a documented process ensures subsequent reviews can easily build on this review.

Insurance values provide an additional rationale for the rehabilitation, restoration and conservation of intact, or relatively undisturbed natural ecosystems. In our review, the values associated with restoration, or the avoidance of loss, of natural ecosystems were universally positive, and in some cases, substantial. More nuanced findings were that (i) the number of studies does not match the frequency or the severity of types of hazards; and, (ii) at a global scale, the geographical focus of studies is not related to the spatial incidence of hazards. The existing literature is also dominated by studies focusing on a specific ecosystem or hazard, such as those based around catchment management and water use planning. These observations suggest that either the funding of academic research is not aligned with exposure to risks, or the pattern may reflect the relatively early stage of ecosystem services research and the longer history of work on water management and floods.

This study also highlights how little research has been conducted thus far to assess the ways in which resilience across ecosystems could be enhanced; despite the fact that a more comprehensive, systems-based approach would be better suited for informing ecosystem management, policy and planning. Furthermore, in many regions multiple hazards can occur simultaneously and/or as a cascade from a single original hazard (e.g. a landslide into a reservoir or glacial lake could lead to dam burst and subsequent downstream flooding). This suggests that the benefit of preventing or avoiding the initial hazard could be substantially magnified if subsequent damage from linked hazards is also avoided. In addition, few studies were explicitly linked to mechanisms through which the insurance value could be 'captured' for wider societal gain (e.g. Jellinek et al., 2013; Mueller, 2014; Mueller et al., 2013). This lack of applied research is a clear gap that should be addressed in future research.

Due to the weaknesses in the existing evidence base, drawing more definitive conclusions (e.g. retaining X ha of forests on mountain slopes delivers $Y per year in avoided damage costs for Z thousand people) from the reviewed studies is difficult. There is great diversity in the methodologies used, temporal and spatial scales, and comprehensiveness across the studies. Many studies did not provide a transparent account of their analytical choices and parameters. This makes the results difficult to compare, transfer and synthesise.

Our review of the existing empirical evidence-base on the insurance value of ecosystems suggest that, as the field develops further, it will be essential that studies are conducted to: 1) provide more consistent and coherent statistics, scenarios and methods across studies and use consistent timeframes to facilitate subsequent reviews and benefits transfer exercises; 2) develop more integrated valuation approaches focusing on the inclusion of insurance value or its disaggregation from other values, such as TEV; 3) better account for climate change; and, 4) clearly define the human "community" benefitting from interventions, as well as the spatial and temporal scales over which these benefits are realised. Following these guidelines will facilitate uptake into policy and practice of insurance value concepts. As the field develops there may be benefit in researchers drawing on best practice from other fields, such as the use and definition of a 'core outcome set' of metrics that are always reported in standardised ways (Webbe et al., 2018; Williamson et al., 2012). As ecosystems continue to degrade, and are relied on by growing human populations for their insurance values, being able to track trends in values, across a diversity of ecosystems and contexts, will provide a powerful argument for the retention, rehabilitation and restoration of natural environments.

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Supplementary Material

Table S1. List of vector-borne diseases included in search terms (adapted from WHO 2017)

Chikungunya
Dengue fever
Rift Valley fever
Yellow fever
Zika
Malaria
Japanese encephalitis
Lymphatic filariasis
West Nile fever
Leishmaniasis
Sandfly fever
Phelebotomus fever
Haemorrhagic fever
Lyme disease
Relapsing fever
Borreliosis
Rickettsial disease
Spotted fever
Q fever
Tick-borne encephalitis
Tularaemia
Chagas disease
American trypanosomiasis
Sleeping sickness
African trypanosomiasis
Plague
Rickettsiosis
Onchocerciasis
River blindness
Schistosomiasis
Bilharzia

Table S2. Full list of the 154 papers for which data were extracted.

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Table S3. Number of studies classified according to CICES Regulation & Maintenance Ecosystem Services.

Code	CICES Regulation and Maintenance simple descriptor	Number
2.2.1.3	Regulating the flows of water in our environment	80
2.2.1.1	Controlling or preventing soil loss	26
2.2.1.5	Protecting people from fire	22
2.2.3.1	Controlling pests and invasive species	17
2.2.2.3	Providing habitats for wild plants and animals that can be useful to us	13
2.2.1.2	Stopping landslides and avalanches harming people	12
2.2.6.1	Regulating our global climate	12
2.2.5.1	Controlling the chemical quality of freshwater	10
2.2.4.2	Ensuring the organic matter in our soils is maintained	7
2.2.3.2	Controlling disease	6
2.2.6.2	Regulating the physical quality of air for people	5
2.2.1.4	Protecting people from winds	4
2.2.4.1	Ensuring soils form and develop	4
2.2.2.1	Pollinating our fruit trees and other plants	1
2.2.5.2	Controlling the chemical quality of salt water	1
5.2.1.2	Physical barriers to flows	1