The contribution of ecosystem services to human resilience

A rapid review

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Key messages

1. Frameworks that link ecosystems services and human resilience are still nascent and the evidence is patchy.
2. The evidence is especially poor when considering the contribution of ecosystem services to the specific processes of building resilience in human systems, such as enhancing flexibility, diversity, cross-scale linkages, safe failure, or self-organisation. When linked to resilience outcomes, there is greater evidence that ecosystems provide significant contributions to basic needs for subsistence, wellbeing, social capital and livelihoods.
3. Ecosystem services have also been shown to reduce exposure to natural hazards, which also contributes to resilient outcomes. This has supported the case to invest in ES through mainstreamed development approaches in the fields of disaster risk reduction and climate change adaptation.
4. There is a strong economic case for investing in ecosystem services for human benefits. The majority of studies find that the costs of ecosystem-based approaches are far outweighed by the benefits.
5. The relative contribution of ecosystem services to human resilience outcomes is much harder to assess. Clearly, many interventions contribute to human resilience outcomes, but it is difficult to differentiate how much ecosystem services contribute to a specific outcome.
6. Governing sustainable ecosystems based on resilience characteristics in linked social-ecological systems is also important to consider if ecosystem services are to deliver human resilience outcomes.

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Summary

Ecosystem services (ES) are the benefits provided by ecosystems that contribute to making human life possible and worth living (MA, 2005). The concept of ES and the benefits these flows bring to humans is a burgeoning area of research. However, the exact ways in which different ES act to enhance people's lives are not yet clear. Human resilience can be defined as the ability of individuals, communities and governments to deal with shocks and stresses. Here, we define human resilience as both a process that delivers a sustainable flow of ES and a set of outcomes that make up resilient lives, communities and countries. While some progress has been made in understanding the links between ES and human wellbeing, Frameworks that link ecosystems services (ES) and human resilience are still nascent. The links between ES and human wellbeing are still not well understood, and links to resilience even less so. The debate around what comprises human resilience in itself is still ongoing in the literature. However, there has been a growth in interdisciplinary science around ES and there is growing evidence that ES support human resilience.

The first section of the review uses this framework as the basis for answering question A, above. The second section of the rapid review deals with the question B, assessing the evidence in terms of quantification and valuation.

To achieve resilience outcomes from ES, these must be delivered sustainably, based on understandings of resilience processes and characteristics that include (Bahadur *et al.*, 2010):

- *Diversity and redundancy* – the variety of components in a system which allow different responses to shocks and stresses, and the ability to lose one component without losing the functions of the system;
- *Participation and community engagement* – the involvement of different social groups and stakeholders ensures a diversity of views and management approaches can be employed to managed shocks and stresses;
- *Polycentrism, decentralisation and flexibility* – governance systems with a multiple bodies to enforce rules, including institutions at local scales and with the flexibility to respond in ways which fit the problems being faced;
- *Learning, experimentation and innovation* – based on the idea that different approaches should be tested in order to learn and innovate, even if failure might sometimes occur; and
- *Connectivity, networks and cross-scalar* linkages – these characteristics help to ensure collaboration across institutions, sharing of knowledge and appropriate responses to shocks and stresses.

Human resilience is concerned with how linked social-ecological systems can deal with shocks and stresses. Human resilience outcomes can be defined as:

- *Providing basic needs for health and wellbeing;*
- *Supporting livelihoods;*

- *Building social capital, stability and security; and*
- *Reducing exposure to natural hazards and enhancing adaptive capacity in a changing climate.*

There is growing evidence in the literature that ecosystems provide the goods that constitute the basic needs for human subsistence, namely food, water and shelter. The contributions of ES to basic needs, health and wellbeing have been well documented for many systems in terms of water provisioning, food production, provision of fuel and fibre, pest and disease regulation, biochemicals and regulation of climate, water and nutrient cycling (MA, 2005). Cultural ES, in terms of identity, sense of place and traditional ecological knowledge, recreational and spiritual values, have been shown as closely linked to subsistence and wellbeing.

Billions of people around the word depend on ES for their livelihoods. Strong and sustainable livelihoods are a vital aspect of human resilience and changes in ES flows can have consequences for livelihoods and vulnerabilities (Folke *et al.,* 2002).

There is less evidence linking ES to social capital, stability and security. However, social capital has been recognized as a critical element of natural resource access and management through institutions and norms (Ostrom, 1990). Declines in ES have been linked to violent conflict and social unrest, and food security is closely linked to human security (IPCC, 2014).

When managed well, ecosystems can mitigate the impact of most natural hazards including landslides, hurricanes and cyclones. There is growing evidence that ecosystem-based approaches to managing disaster risk and mitigating disaster impacts can make a valuable contribution to human resilience (Sudmeier-Rieux *et al.*, 2006). Similarly, ES affect the adaptive capacity of communities in a changing climate, leading to greater attention towards ecosystem-based adaptation (EbA) approaches (Vohland *et al.*, 2012).

There is a large literature on valuing ES, typically using methodologies to establish human use values in monetary terms. There are several global initiatives seeking to add evidence to this discussion, including The Economics of Ecosystems and Biodiversity (TEEB) and the Natural Capital Project.

The majority of the literature on valuation is very context specific, using case studies to link specific ES to a specific human outcome. A key finding from the literature is that majority of ES projects have benefits that outweigh costs, and therefore warrant investment. Further, investments in activities that improve incomes are very likely to result in helping people to rebound more easily from a crisis, as income and assets are key to determining factors of resilience.

A number of studies have undertaken comparative analyses between ecosystem-based and other approaches to building resilience. These studies allow for prioritisation of ecosystem-based approaches over others, but are limited in their number. This case has been made most strongly for freshwater systems, coastal planning and protection and food security.

The argument to invest in ES as part of a mainstreamed development approach has been used in the fields of disaster risk reduction (DRR) and climate change adaptation (CCA), by demonstrating the losses that can be avoided by mainstreaming DRR and CCA into wider development planning. For example, TEEB's 'GDP of the Poor' analysis shows that if ES are not mainstreamed into wider development work, at least half of the gross domestic product (GDP) of poor people who depend on natural resources and ES for their livelihoods will be put at risk, undermining all other efforts at poverty reduction.

There are a number of characteristics of ES that make valuation of the benefits of ecosystem-based approaches compared to other approaches difficult. These include the timeframe over which ES benefits are realized, which are typically longer, and the distribution of these benefits across groups of people. Nonetheless, there is a strong economic case for investing in ES, as the majority of studies find that the costs of ecosystem restoration and protection are far outweighed by the benefits. According to one study, coastal wetlands, inland wetlands and tropical forests offer the largest potential gains for investment in ecosystem restoration, where benefits are based on the monetary value of the total bundle of ES provided by the restored ecosystem (De Groot *et al.*, 2013).

The relative contribution of ES to human resilience outcomes is much harder to assess. Many factors can contribute to human resilience outcomes, but it is difficult to attribute how much ES contribute to a specific outcome. While there is a strong argument for mainstreaming ES into any attempts to build resilience in theory, there is little evidence of how this can be assessed in practice. The DRR and CCA agendas have very successfully created arguments for integrating risk management into development approaches and a similar argument could be made for ES.

Table 1: Summary of ecosystem services contribution to human resilience outcomes

ES **Resilience**	**Provisioning**	**Regulating**	**Cultural**
Basic needs, health and wellbeing	• Food production by agro-ecosystems underpins food security • Food production (protein) by aquaculture and fisheries • Forests and mountains produce water used to support agriculture • Water supply supported by vegetation, soils and microorganisms • Fuel and fibre for shelter, cooking and heating • Biochemicals with medicinal value derive from a range of ecosystems • Crop genetic diversity increases and sustains food production and quality	• Climate regulation by oceans, forests, • Carbon storage in soils, vegetation and oceans • Soil biodiversity regulates soil ecosystem for primary production and nutrient cycling • Water regulation and purification • Pollination by animal vectors • Biological control of crop, livestock and human diseases • Health benefits from air and water purification	• Foster sense of place of intrinsic value to all societies • Cultural identity and wellbeing • Traditional ecological knowledge enables use of resources and survival • Food preferences linked to food provision, wild foods as important reserves • Relatively intangible in general • Culture can mediate access to resources creating winners and losers • Psychological/health benefits from access to green open space in urban areas
Livelihoods	• Fisheries and agro-ecosystems vital to livelihoods and economies across the world • Sustainable livelihoods supported by natural capital • Fibre and fuel products that generate income (e.g. timber, biofuels, etc.), but values vary • Natural resources are basis of industry, manufacturing, trade, medicine and tourism • Health and wellbeing from access to green open space can increase economic productivity • Biodiversity often yields high-value incomes from tourism and related activities • Freedom of choice to pursue livelihoods	• Water provision, pollination and soil quality are all crucial for food security but often do not accrue financial benefits for small-scale farmers and pastoralists • Biological control of agricultural pests reduces economic losses • Species and biodiversity can act as bio-indicators of environmental stress	• Cultural status linked to biodiversity and can enable or impede livelihood opportunities • Institutions and norms have evolved in cultures closely linked to environments • Such cultural diversity can be of tourism value • Nature-based tourism and recreational value are basis of many livelihoods • Aesthetic value of ecosystems contributes to use of open spaces and other nature-based facilities

Social capital, stability and security	• Natural resource access and management has evolved with institutions particular to systems • Declines in ES can lead to violent conflict and social turmoil if scarce • Food security and human security are linked • Green open space in urban areas can reduce crime and aggression	• Climate change and breakdowns in climate regulation services are increasingly becoming security problems • Environmental change can impact on social cohesion and institutions • Regulation of disease ecology prevents breakdown of social order/stability • Many customs and institutions have been established to manage regulating ES	• Natural resource markets can shape social relationships at local and global levels • Demands for natural resources shifting through urbanisation, etc. • Recreational, spiritual, mental health and amenity values
Reduced exposure and enhanced adaptive capacity	• Strong and sustainable livelihoods build resilience to recover from disasters • Diverse food products resilient to shocks e.g. pest outbreaks, drought, etc. • Fibre and fuel can be a cause of disaster risk e.g. wildfire in shifting landscapes • Provision of food, water and energy important for enhancing adaptive capacity in a changing climate	• Ecosystems can act as barriers or buffers to extreme events and natural hazards • Economic losses and deaths can be reduced by provision of such ES • Regulating ES is also core to adapting to long-term stresses e.g. climate change	• Perceptions and responses to natural hazards influenced by cultural and social factors • Cultural factors and traditional ecological knowledge can reduce risk and build adaptive capacity

Context, conceptual approach and methods

Use of the concept of resilience is growing rapidly in both policy and academic circles. As a result, there is little agreement on how resilience should be defined and consequently measured, not least because resilience may differ depending on context, space and time. At the same time, there has been increased interest in the past decade in approaches that link ecosystems with the benefits they contribute to making human life both possible and worth living. The Millennium Ecosystem Assessment, published in 2005, aimed to provide scientific information for decision-makers on the consequences of ecosystem change for human wellbeing (Carpenter *et al.*, 2006), but there have been very few linkages made to human resilience.

Responding to this gap, this rapid review summarises the extent of this evidence, framed around the questions:

1. How do ecosystems contribute to human resilience?

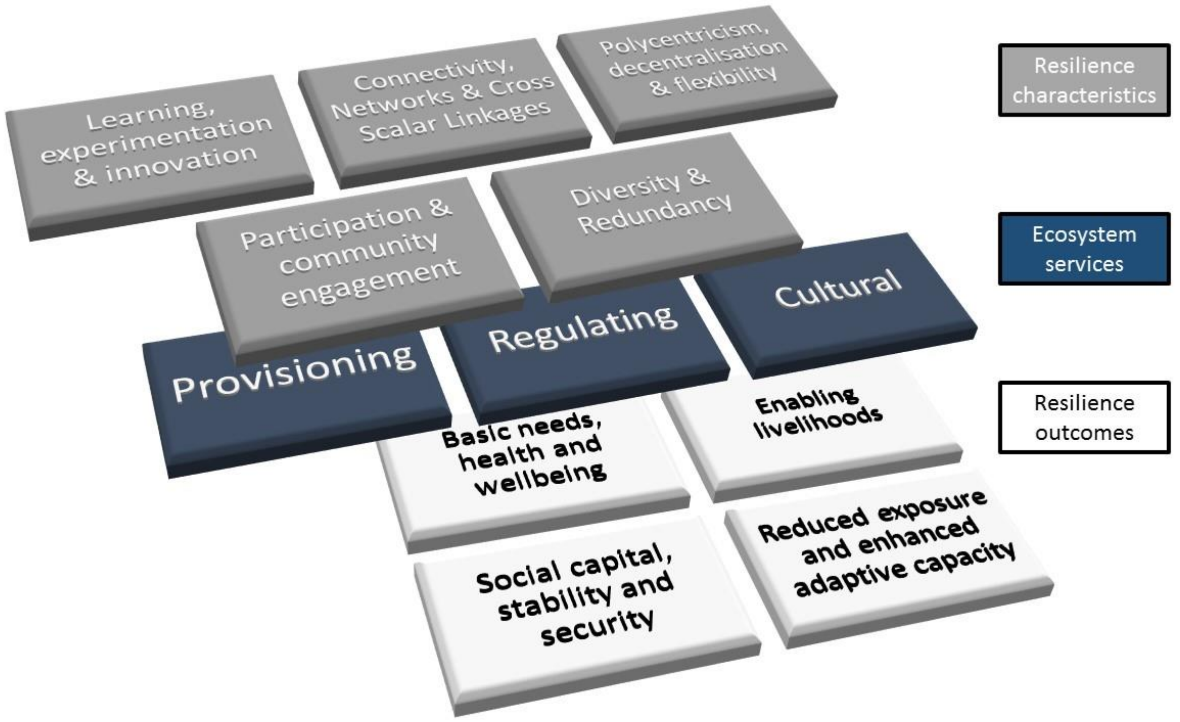
2. How can we measure/quantify the value of ecosystems in building resilience?

The review captures key academic and grey literature linking ES and resilience through the use of initial searches on Science Direct and Google Scholar using search protocols outlined in Annex 1. This was followed by a processes of snowball sampling and recommended readings from the panel of international experts who generously gave their time for the study (see Acknowledgements section prior to references). The review does not attempt to be comprehensive or systematic, but rather to provide a rapid assessment of the state of evidence on the linkages between, and measurement of, ecosystems and human resilience.

The lack of literature linking ecosystems with resilience-building processes led us to focus on outcome-based resilience, as reflected in some of the emerging innovative operational resilience frameworks, such as the Arup-Rockefeller Resilient Cities Framework. As such, our conceptual approach (see Figure 1) overlays the characteristics of resilience thinking for governing sustainable, resilient ecosystems that can provide a reliable flow of ES to support human development. It then links the provision of ES (based on Millennium Ecosystem Assessment definitions) with a set of resilience outcomes, as reflected in some of the emerging innovative, operational resilience frameworks, such as the Arup-Rockefeller Resilient Cities Framework. These resilience outcomes include: basic needs, health and wellbeing; social capital, security and stability; enabling human livelihoods; and, reduced exposure to hazards or enhanced adaptive capacity for a changing climate.

The first section of the review uses this framework as the basis for answering question A, above. The second section of the rapid review deals with the question B, assessing the evidence in terms of quantification and valuation.

Figure 1: Conceptual Framework linking human resilience and ecosystems



Part One: Exploring the contribution of ecosystems to building human resilience

Which resilience characteristics are important in social-ecological systems?

This report outlines the evidence in the literature that ecosystems can support human resilience through the supply of a range of provisioning, regulating and cultural services. Ecosystem services (ES) are the benefits provided by ecosystems that contribute to making human life possible and worth living (MA, 2005). The concept of ES and the benefits these flows bring to humans is a burgeoning area of research. However, the exact ways in which different ES act to enhance people's lives are not yet clear. Human resilience can be defined as the ability of individuals, communities and governments to deal with shocks and stresses. Here, we define human resilience as both a process that delivers a sustainable flow of ES and a set of outcomes that make up resilient lives, communities and countries. While some progress has been made in understanding the links between ES and human wellbeing, frameworks that link ecosystems services (ES) and human resilience are still nascent. The debate around what comprises human resilience in itself is still ongoing in the literature. However, there has been a growth in interdisciplinary science around ES and there is growing evidence that ES support human resilience.

Achieving is done primarily by examining resilience outcomes and their links to ES. However, this depends on the sustainable management of ES, which itself draws on a range of process-based characteristics of resilience (Bahadur *et al.*, 2010). This section therefore briefly outlines these characteristics, linking to ecosystems and human resilience thinking.

Resilience Process 1: Diversity and redundancy

Diversity is cited very frequently as a key tenet of resilience thinking and it has been shown to support resilience in a range of different ways (Carpenter *et al*. 2001; Folke, 2006; Holling, 1973; Resilience Alliance, 2002). Holling (1973) was one of the first to highlight the manner in which maintaining diverse functional groups within an ecosystem kept them healthy and supported their sustainability. Simply put, different sets of organisms perform different functions in an ecosystem that help balance the vital elements of the system in a way that prevents the depletion of key ecological resources. Biggs *et al.* (2012) add the idea of response diversity, outlining the manner in which a higher functional diversity allows an ecosystem to be more resilient to disturbances also because different organisms all respond to disturbances in different ways.

Therefore, even if some organisms perish others will survive and prevent the entire system from sliding into collapse. This 'redundancy' is then vital to the ability of ecosystems to function through shocks and stresses as it allows certain elements to fail in a way that does not jeopardize the wider system (Rockefeller Foundation, 2014). A number of theorists have extrapolated the principle from this to argue that, in a policy context, this should be interpreted as the need to bring additional constituencies into the policy arena, each of whom contribute their points of view on how to keep the diverse elements of a system healthy and sustainable (Berkes, 2007; Biggs *et al.,* 2012).

Resilience Process 2: Participation and community engagement

Community engagement, ownership, participation and indigenous/local knowledge are commonly stressed in literature on resilience (Manyena, 2006; Mayunga, 2007; Ostrom, 2009; Nelson *et al.,* 2007; Dovers and Handmer, 1992; Berkes, 2007; Biggs *et al.*, 2012, Osbahr, 2007). Biggs *et al.* (2012: 436) note that participation is important to successful management of ecosystems as it helps 'to improve legitimacy, facilitate monitoring and enforcement, promote understanding of system dynamics, and improve a management system's capacity to detect and interpret shocks and disturbances.' The participation of communities benefiting from ecosystems services is important to their management because these systems are dynamic, with varying degrees of quick changes and gradual shifts.

Therefore, groups that rely on these systems would have a much greater appreciation of negative/detrimental changes occurring within them, as well as an inherited understanding of methods of rectifying these, as compared with parties that are wholly external to the local context (Norris *et al.* 2008). Participation of users in ecosystem management is also seen as key to the health of these systems because it enhances the degree to which these users take ownership of them (Ostrom, 2009). Simply put, the responsibility of maintaining the health of ecosystems reduces the unsustainable exploitation of ES by any single user. At the same time, the close integration of 'use' with 'management' also helps share information and raise awareness of all participants on the issues with disparate parts of the system that need to be addressed in order to ensure the uninterrupted flow of ES (Rockefeller Foundation, 2014). Much research has been done to explore the ways in which 'co-management' of natural resources between government and community-based institutions can lead to more sustainable outcomes, i.e. in the management of fisheries (Pomeroy and Berkes, 1997), wildlife (Gibson and Marks, 1995) and a range of other natural resources (Olsson *et al.*, 2004).

Resilience Process 3: Polycentricism, decentralisation and flexibility

The principles of polycentricism and decentralization are also seen to be key to managing ecosystems in way that they sustainably provide services to enhance human resilience (Dovers and Handmer, 1992; Folke, 2006; Osbahr, 2007; Ostrom, 2009; Biggs *et al.*, 2012; Rockefeller Foundation, 2009). Osbahr (2007, p. 14), writing in the context of governing social-ecological systems highlights the need 'for polycentric and multi-layered institutions to improve the fit between knowledge, action and the context in which societies can respond more adaptively at appropriate scales.'

Biggs *et al.* (2012), speaking more directly in the context of ecosystem management, highlight the same principle, but provide a different interpretation by highlighting that governance at smaller scales allows the development and deployment of management approaches that are more adapted to the local context. In sharp contrast to a 'command and control' approach to management, decentralized management permits the incorporation of 'scale specific knowledge' in key decisions around maintaining the health of ecosystems (*ibid.*). This is critical to ensure that any system to manage ecosystems has the flexibility needed to make decisions, change courses of action and switch tactics during emergent/dynamic situations to ensure that the system does not tip over into disfunctionality (Nelson *et al.*, 2007).

Resilience Process 4: Learning, experimentation and innovation

Learning and experimentation have been understood as critically important to any approach to managing ecosystems, so as to ensure that they continue to support human resilience (Biggs *et al.*, 2012). While different experts have highlighted the importance of these in different ways, the key strain running through all their arguments is that change and uncertainty are inevitable in ecosystems, therefore continual learning and the revision of knowledge is key to ensuring their effective management (*ibid*). This principle becomes particularly valuable in circumstances where ecosystems are recovering from disturbances, as it is vitally important for those managing them to ensure that they are not 'restored' as that would imply that they are as vulnerable to the same disturbance again.

Instead, learning from disturbance must take place so as to ensure that the system 'bounces back better' and can withstand a similar disturbance should it strike again (DFID, 2011). This principle is enshrined within the concept of 'adaptive management' that is seen as an effective method to ensure the sustainability and health of any systems as it is hinged on iterative learning cycles that permit a change of tactics, approaches and arrangements as circumstances change (Gunderson and Holling, 2001). Continual learning through adaptive management is also important because it facilitates a process of experimenting with innovative approaches to managing ecosystems better, permitting a swift rejection of ineffective tactics and an adoption/institutionalization of those that support the system in functioning through disturbance (Carpenter *et al.*, 2001).

Resilience Process 5: Connectivity, networks and cross-scalar linkages

'Connectivity is defined as the manner by which and extent to which resources, species, or social actors disperse, migrate, or interact across ecological and social "landscapes",' (Biggs *et al.,* 2012: 427). This principle was highlighted by Holling (1973) when he compared the resilience of fish stocks in a closed, local ecosystem – like that of a lake – with that of pest populations, which are highly dispersed in space yet intrinsically connected, to find that the latter are far more resilient. This was primarily because this made it more difficult for a single disturbance to obliterate the entire species. Taken in the context of managing ecosystems, connections and networks can enable resilience by channelling resources and information swiftly to enable a system to either recover or prepare for a disturbance (Nelson *et al.*, 2007).

Twigg (2009) illustrates this in the context of building the resilience of communities to disasters. He argues that linkages across scales of governance in the field of early warning systems has led to dramatic improvements in the ability of communities to be more resilient to disasters (*ibid.*). This principle is evident in the highly successful Bangladesh Cyclone Preparedness Program, where an early warning system run by the central government dovetails into systems of response and preparedness at the sub-national and local levels of governance. Another example at a smaller scale is the Surat Early Warning System, supported through the Asian Cities Climate Change Resilience Network (ACCCRN), which builds on connections made through previous work to improve implementation and operation (Bhat *et al*., 2013). It is easy to see how such a network can be beneficial in a variety of contexts including in the management of an ecosystem to ensure that it continues to provide services through a variety of shocks and stresses. The two key principles regarding connectivity are that: first, those managing ecosystems should aim for functional connectivity (similar to functional diversity discussed earlier) and second, networks across scales should be established to support the process of ecosystem management itself.

How do ecosystem services contribute to human resilience?

This section assesses the linkages between different ES and human resilience by working through the linkages to the resilience outcome categories outlined in the conceptual framework. Framing these sections is an acknowledgement that, while sustained flow of ES brings tangible benefits to humans, some ecosystem states or bundles of services are more desirable to some people than others (Robards *et al.*, 2011).

The use of ES involves asymmetries and power dynamics (*ibid.*), and different ecosystems services can create wellbeing for different groups of people, thus creating winners and losers (Daw *et al*., 2011). In these cases, trade-offs in the provision of one ecosystem service at the expense of another can occur (Rodriguez *et al.*, 2006). Individual contexts and needs modify how ES contribute to wellbeing (*ibid.*). Examples from coastal systems point to the complexity of wellbeing and the difficulties in quantifying or measuring ES' contribution to wellbeing (Abunge *et al.*, 2013).

Resilience Outcome 1: Basic needs, health and wellbeing

Ecosystems provide goods that constitute the basic needs for human subsistence, namely food, water and shelter. These are constituents of human wellbeing, as is health, characterized as strength, feeling well and access to clean air and water (Millennium Ecosystem Assessment, 2005). As well as outlining human wellbeing in terms of physical provision of goods, the 2005 Millennium Ecosystem Assessment (MA) also recognizes the importance of aesthetics, spiritual and cultural services to human wellbeing.

The contributions of nature to the basic needs, health and wellbeing have been well documented for many systems in terms of food production, water provisioning, provision of fuel and fibre and regulation of climate, water and nutrient cycling. As defined by the MA, there is a fourth category of ES, supporting services, which produce the conditions for all other provisioning, regulating and cultural services. While this category is not included in the conceptual framework shown in Figure 1, it is important to recognize that supporting services are responsible for the primary production, nutrient cycling and soil formation that underpin the contributions of ecosystems discussed below.

Provisioning ES

Food security is increasingly important to human resilience, as demand increases and commodity markets become more volatile (De Schutter, 2009). Agro-ecosystems, ranging from small-holdings to commercial scale, provide food for human consumption and underpin global food security (Boelee, 2011; Elmqvist *et al.*, 2011). As well as production of sufficient food in terms of quantity, the nutritional quality of food produced is also critical to human health and an important component of food security (FAO, 2011). Much of the Earth's land surface is used for food production through crop cultivation and/or livestock rearing. Marine and freshwater fisheries and aquaculture also provide large sources of protein to the global population (FAO, 1997). Aquaculture depends on nutrient recycling and water purification services in coastal areas and inland water bodies (Outeiro and Villasante, 2013). In urban contexts, ecosystems can help to meet energy needs and support agriculture (CBD, 2012).

As well as production of sufficient food in terms of quantity, the nutritional quality of food produced is also critical to human health and an important component of food security (FAO, 2011). A range of ecosystems provide both wild and domestic sources of nutrition for humans (Myers, 2013). Where these resources are in decline, malnutrition can occur. For example, in coastal communities relying on dwindling fisheries for protein intake (*Ibid.*). For communities across the world, nutritional needs can be met through wild products identified and located through ecological knowledge, another ecosystem service (De Clerck, 2011; De Clerck *et al.*, 2011).

Globally, water is used predominantly for agriculture including livestock production, followed by industry and domestic uses (Elmqvist *et al.*, 2011). Forest and mountain ecosystems act as source areas for most renewable water supplies, and regulate pollution and water quality. The link between regulation of water supply and water quality is strong (*ibid.*). Vegetation, soils and soil organism activity are major determinants of water flows and quality, and micro-organisms play an important role in groundwater quality. While the general relationship between more intact biodiversity and water regulation is understood, the relationships between discrete species and changes in biodiversity with changes in water regulation are not.

Land use change, particularly deforestation, has the potential to affect the capacities of ecosystems to regulate and provide freshwater, which can be difficult to reverse (Gordon, 2003). Large-scale land use change has the potential to affect vapour formation and rainfall patterns in locally specific and highly variable ways (*ibid.*). Rain-fed agricultural systems will potentially be influenced, in turn impacting on food production and quality (*ibid.*).

Agro-ecosystems can also interplay with human resilience in negative ways; for example, by impacting on ES nearby through nutrient pollution and barriers to migration and dispersal of organisms, sedimentation of waterways and loss of wildlife habitat (Power, 2010).

The provision of fuels and fibres including timber, cotton, sisal, sugars and oils is an important ecosystem service for humans. Such natural materials are used for construction of shelter and fuel for cooking and heating (MA, 2005). Biochemicals produced by plants, animals and microorganisms are high-value medicinal resources for the production of pharmaceuticals, as well as pesticides and other products (*ibid*.). Pharmaceutical compounds have been derived from the range of ecosystems, including oceans, coastal areas, freshwater systems, forests, grasslands and agricultural land (*ibid*.).

Crop genetic diversity is critical for increasing and sustaining production levels and nutritional diversity throughout the full range of agro-ecological conditions (FAO, 2010). Genetic diversity within crops contributes to food security by increasing yields and nutritional values. Humans have had a long history of improving varieties and replacing local varieties of domesticated plant species with high-yielding crops, thus eroding genetic resources. Agricultural genetic diversity also provides services for genetic diversity in non-domesticated species of plants, animals and microorganisms that are linked to them within ecosystems. Advances in genetic modification are opening up opportunities to increase these effects through preservation of genetic diversity in gene banks and creation of improved strains or breeds. Genetic diversity of crops also decreases susceptibility to pests. Genetic resources in crop plants, livestock and fisheries will be increasingly important for resistance to diseases and adaptation to novel climatic conditions.

Access to green space has been linked to reduced mortality, improved perceived and actual general health and psychological benefits (Tzoulas *et al.*, 2007; CBD, 2012).

Regulating ES

Climate regulation services provide the conditions conducive to maintenance of life on Earth. The atmosphere and Earth's surface reflect and absorb solar radiation, the oceans and vegetation absorb carbon dioxide, and methane and nitrous oxide are regulated by soil microbes.

Soil biodiversity performs vital functions to regulate the soil ecosystem for primary production. Increased biodiversity often enhances productivity. High functional diversity of invertebrate decomposers provides supporting services in nutrient cycling and therefore primary production, and high structural diversity of plant cover contributes to rainfall water regulation and soil conservation and therefore primary production (MA, 2005). Similarly, the capacity of the oceans to regulate climate is dependent on their biodiversity. However, a current question in ecological research is the extent to which biodiversity determines ecological function, resilience and the provision of ES (Fisher *et al.*, 2014). While a clear positive link has been demonstrated in the literature, complex dynamics in space and time are not well understood (Norgaard, 2010, Fisher *et al.*, 2014).

Ecosystems also play a vital role in cycling and storing carbon for climate regulation. Vegetation, particularly trees and forests, store carbon in biomass. All soils store carbon but to different extents. Peat soils constitute the single largest store of carbon in terrestrial ecosystems and potential climate change impacts on these will be critical in terms of the global carbon cycle. Carbon dioxide exchange with the oceans is larger than with terrestrial ecosystems and marine ecosystems also sequester carbon and emit aerosols.

Forests are the only ecosystem that store carbon in their biomass in excess of that sequestered in soils. The potential for grassland systems to sequester more than 30% of the world's soil carbon in addition to substantial above-ground carbon, if managed sustainably, is also being recognized (Neely *et al*., 2009). Such management will also provide a series of resilience co-benefits in terms of productivity, livelihoods and maintenance of cultural services (Neely *et al.*, 2009; Rumbaitis del Rio, 2012). Agricultural systems generally have low soil carbon storage capacity compared to natural ecosystems, due to intensive production methods (Elmqvist *et al.*, 2011).

Between 50% and 71% of the carbon sequestered in oceans (which totals up to 55% of total sequestration) is captured by coastal vegetation (Nellemann *et al.*, 2009). Rates of sequestration and storage by coastal vegetation can be as much as or higher than rates in tropical rainforests or peatlands (*ibid*.). There is growing interest in the concept and potential of 'blue carbon' and the sequestration of carbon in coastal vegetation, including mangroves, seagrasses and salt marshes, and the sediments they grow on. One study has estimated that 0.15-1.02 billion tons of carbon dioxide are released annually from coastal sediments due to habitat destruction (approximately 3-19% of emissions from deforestation globally) (Pendleton *et al*., 2012). The economic damage resulting from these emissions is estimated at between US$6 billion and US$42 billion annually (*ibid*.).

Climate, soil and water regulation to provide suitable conditions for food production (quantity) and food quality in certain locations at certain times (affecting food access) influences all aspects of food security (FAO, 2011, Poppy *et al.*, 2014). Land use change to and from agriculture affects levels of regulating ES, including carbon dioxide cycling, nitrogen flow and freshwater consumption. Climate change and land use change will interact to impact on the provision of stable climatic conditions. Offshore aquaculture intensification will also affect the cycling of typically nutrient-poor water and thus regulatory services (Outeiro and Villasante, 2013).

Ecosystems play a vital role in water quantity and quality for human consumption and crop and livestock production. Both rural and urban settlements depend on the capture of surface water in watersheds to regulate supply, and water purification services to regulate quality (McDonald *et al*., 2011).

Most crops and plant species across all ecosystems rely on pollination by animal vectors. Bee species are the dominant pollinators of crops, and birds, bats, moths, flies and other insects also perform this service. Ecosystems provide suitable habitats for these important species to nest and forage. A diverse assemblage of pollinators provides resilience to shocks and stresses, although there are likely thresholds of land use intensification, climate change and alien species invasion/establishment beyond which pollinator services will be lost (Vanbergen and Insect Pollinators Initiative, 2013). This would have serious implications for food security (*ibid.*). Biological control of plant pests is provided by predators and parasite species, and this can improve crop yields and prevent pest epidemics (Power, 2010).

Ecosystems contribute towards several regulatory services that are important for human health and wellbeing. Vector-borne diseases, including dengue fever and malaria, are effectively controlled by ecological regulation (MA, 2005). In recent years, environmental degradation has led to the increased incidence of such diseases, highlighting the link between this ecosystem service and human resilience. The Intergovernmental Panel on Climate Change (IPCC) finds with very high confidence that the health of human populations is sensitive to shifts in weather patterns and climate change (IPCC, 2014, Chapter 11). Health can be damaged by ecological disruptions brought on by climate change (e.g. crop failures, shifting vectors of human, crop and livestock diseases) (*ibid*.).

Furthermore, degradation in ES, such as changes in the species richness – the relative abundance of species within an ecosystem – can alter the ecology of diseases (Pongsiri *et al.*, 2009; Myers *et al.*, 2013). This effect has been shown for West Nile virus in the United States and Chagas disease in Latin America (*ibid*.). More research is needed to understand these dynamics in the context of other stressors, such as climate change (Myers and Patz, 2009).

In urban areas, vegetation helps to significantly reduce air and noise pollution, positively affecting health. Green spaces in urban areas can also mitigate against temperature rises and the 'heat island' effect (IPCC, 2014). There are also direct health benefits, including mitigation of asthmatic conditions, stress and anxiety, mental health and general wellbeing. The links between particular species or biodiversity and environmental quality have not been well described (Elmqvist *et al.*, 2011).

In cities, ecosystems can regulate climate, protect against hazards, meet energy needs, support agriculture, prevent soil erosion, regulate wastewater and offer opportunities for recreation and cultural services. Importantly, urban ecosystems offer risk reduction services through storm water regulation, flood control and mitigation of coastal storms/wave attenuation. These play a key role in reducing vulnerability to storms, floods and sea level rise in urban contexts (Rockefeller Foundation, 2009). In brownfield sites, novel functioning ecosystems generate services that contribute to the wellbeing of urban populations, as well as supporting distinct assemblages of species and biodiversity, which provide opportunities for recreation, health and community cohesion (CBD, 2012).

Cultural ES

While cultural ES have been variously defined since the MA was published in 2005, they are generally agreed to be intangible in comparison to provisioning and regulating services (Milcu *et al*., 2013). Nonetheless, all societies value these ES, and ecosystems play an important role in fostering a sense of place and are therefore of intrinsic value (Elmqvist *et al.*, 2011). Cultural and recreational services based on nature are most strongly associated with less intensively managed areas (*ibid*.). In tightly-linked social-ecological systems, such as traditionally managed rangelands, arctic tundra, forests or small-scale agricultural systems and fisheries, cultural ecosystem series are essential to cultural identity, wellbeing and even survival (Brown and Neil, 2011, Cunsolo Willox *et al.*, 2012). In more industrialized or urban contexts, cultural services are also considered very important, but tend to focus on recreation or aesthetic services (Milcu *et al*., 2013). There is also strong evidence that green open space plays a positive role in enhancing wellbeing associated with sense of place and the psychological benefits have also been shown (Elmqvist *et al.*, 2011). Indeed, access to green space has been linked to reduced mortality, improved perceived and actual general health and psychological benefits (Tzoulas *et al.*, 2007; CBD, 2012).

Traditional ecological knowledge (TEK) is defined as a cumulative body of knowledge, practices and beliefs about the relationships of living beings, including humans, to one another and the environment (Gadgil *et al.*, 1993). It is argued in the literature that TEK is the product of the ecosystems in which societies live and interact on a daily basis (Gadgil *et al*., 1993; Berkes, 2003; Folke, 2004). A study comparing small-holder farmer responses to pest outbreaks, climate variability and other disturbances in Tanzania and Sweden, found that both communities developed practices in similar ways that increased their capacity to deal with shocks and stresses and that promoted biological diversity (Tengö and Belfrage, 2004). In this sense, TEK makes an important contribution to the resilience of food production in small-scale agricultural systems.

Food preferences arising from cultural differences are important drivers of food provision (MA, 2005); for example, increased per capita consumption of fish worldwide, increased meat consumption in emerging economies, and wild foods being locally important in many developing countries. Wild foods hold cultural significance for local communities across the range of ecosystems (Barucha and Pretty, 2010).

Resilience Outcome 2: Livelihoods

Worldwide, billions of people depend on natural resources for their livelihoods. The majority of those living in poverty particularly rely on ES for income generation opportunities. The MA defines the constituents of livelihoods as the basic materials for a good life (i.e. adequate livelihoods, access to goods) and freedom of choice (MA, 2005). Strong and sustainable livelihoods are a vital aspect of human resilience and changes in ecosystem service flows can have consequences for livelihoods and vulnerabilities (Folke *et al.*, 2002).

Provisioning ES

The importance of natural resources to livelihoods has been recognized in the literature for several decades. For instance, the sustainable livelihoods approach (Chambers and Conway, 1992) recognized that most rural livelihoods rely on natural resources to some extent. The capacity of livelihoods to cope with and recover from shocks and stresses is central to this definition (Conway, 1987, Holling, 1993, Scoones, 1998). It was implied in the sustainable livelihoods approach that depleting natural resources will reduce the capacity for livelihoods to withstand shocks and stresses and thus their sustainability.

Most ecosystems are important in producing fibre and fuel that support livelihoods. Production of wood and non-wood forest products is the primary commercial function of approximately 35% of the world's forests, while more than half of all forests are used for such production in combination with other functions, such as conservation and recreation (Elmqvist *et al.*, 2011). There is growing demand for biofuel production, through cultivation of biomass crops or diversion of agricultural land from food production to biofuel manufacturing. Algae is also being cultivated for biofuels (Adams *et al*., 2009). The downside of harnessing ecosystems to support livelihoods in this way is that they are not often managed for bundles of ES. For example, timber production is often the sole management objective, overlooking the valuable services that are co-produced with timber, such as watershed protection, habitat provision and climate regulation (Elmqvist *et al.*, 2011).

The assumption that species biodiversity as an ecosystem good can help to alleviate poverty is not well supported (Roe, 2014). There is much evidence that biodiversity does produce specific goods that can generate cash income, food or fuel (e.g. forest products act as safety nets for those communities that inhabit forest areas (Fisher *et al.*, 2014)). It is important to note that these products may differentially alleviate poverty (e.g. firewood and food products may produce lower incomes than timber or employment in nature reserves (Fisher *et al*., 2014)). However, there are few studies that show the role of biodiversity in underpinning the ES poor people depend on. Even fewer look at the benefits of diversity as a form of adaptive capacity (*ibid.*; Leisher *et al.,* 2010). More research is needed in this area to elucidate the links between biodiversity and poverty.

Many rural and coastal livelihoods are dependent on ES, with billions of people involved in agriculture and fishing across the world (Rockefeller Foundation, 2013; WWF-UK, 2014). More than 70% of poor people live in rural areas and depend heavily on ES (Sachs and Reid, 2006). Agricultural development is a primary means of poverty reduction in rural developing country contexts (Acharya, 2006). The strong link between the state of ecosystems and the development potential of rural areas, biodiversity conservation is increasingly combined with rural development (Sachs and Reid, 2006).

The productivity of agro-ecosystems relies on provisioning – as well as regulating – ES, including fertile soils and provision of water (FAO and IFAD, 2008). Fisheries and aquaculture employ 55 million people and support the livelihoods of 660 million-820 million people around the world (Rockefeller Foundation, 2013). These production systems are vital to the nutritional needs, livelihoods and economic growth of many countries, but are increasingly under threat from degradation, pollution and climate change (*ibid*.).

Peri-urban and urban agriculture also contribute to the food security of urban areas and can help to generate incomes for urban households. Many cities and urban areas have good conditions for agriculture (e.g. Kampala, Uganda). Urban areas and urbanization also create markets that benefit food production and agri-diversity through local food preferences (e.g. local rice strains in Vietnam are marketed in urban areas) (CBD, 2012).

Most communities and economies strive to maintain a diverse range of livelihood options as buffers against external shocks and stresses (MA, 2005). Natural resources also form the basis of industry, trade, medicines and tourism, all of which provide livelihoods for people in developing and developed countries around the world (WWF-UK, 2014). In urban settings, the health and wellbeing benefits conferred by green open spaces in turn can enhance economic productivity and prosperity in cities (Elmqvist *et al.*, 2011). The psychological benefits derived from green open space in urban areas have been shown to have a positive effect on economic productivity. Property prices have been shown to increase with proximity to green open space (Saraev, 2012). Clean air and water are important public health concerns in urban areas.

Wildlife, including plants and animals, often yield high-value economic goods and services in terms of tourism and other products (e.g. trophy hunting, hides, research activities (Emerton, 2001)). In southern Africa, for example, nature-based tourism is reported to generate as much revenue as farming, forestry and fisheries combined (Scholes and Biggs, 2004). Globally, tourism is estimated to contribute as much as 10% of GDP, with nature-based tourism the fastest growing sector (Balmford *et al.*, 2009). These services often form the basis of relatively high-value income generation for local communities, although there are significant political economy issues surrounding tourism in developing countries (*ibid.*). Wild harvest products provide vital protein and nutrients and provide for basic food security needs (fish, wild meat, fruits, nuts, tubers).

Regulating ES

The regulating ES outlined in the previous section underpin natural resource-based livelihoods, which predominate in developing countries (UN, 2014). For example, agricultural production forms the livelihoods of most of the 1.4 billion people living in poverty (IFAD, 2013).

Water provision, pollination and maintenance of soil fertility are important ES to be conserved for future food security. However, small-scale farmers and pastoralists do not receive financial benefits for conserving these ES for other users, nor do they commonly incorporate the full economic value of ecosystems into their production decisions; instead, they simply maintain ES them as valuable for their own food production. Because the value of preservation of ES is not built into food production costs, the current food system does not contribute optimally to resilience (Munang *et al.,* 2014). In Uganda, conventional preparation of an acre of land for agriculture costs approximately US$100, but with conservation agriculture measures this cost is reduced to only $US 25 (Munang *et al.*, 2014). In addition to financial benefits, productivity of crops has increased, the use of environmentally harmful and costly fertilizer and pesticide inputs has decreased, and farmers can also invest more time in other livelihood activities to increase their resilience (*ibid.*).

Agricultural pests cause significant economic losses worldwide, with more than 40% of food production lost to insect pests, plant pathogens and weeds (Pimentel and Peshin, 2014). Ecosystems provide natural controls on pests, in the form of predator and parasite species, and biochemical inputs to artificial pesticides. This disease regulation service will be increasingly important in the future as climate change alters the incidence of pests and susceptibility of species to infestation. Some species of animals and fish provide regulatory services in terms of disease control. For example, mosquitofish feed on and control aquatic disease vectors in tropical ecosystems (Moyle and Moyle, 1995).

Related to this, some species, assemblages and habitats can act as bioindicators of ecosystem stress, acting as early warning systems for reduced resilience. For example, lichens can indicate levels of air pollution in a location and top carnivores, including birds of prey, can indicate the presence of environmentally damaging compounds by bioaccumulation (Tataruch and Kierdorf, 2003). Fish species' richness and abundance can be used to monitor water quality (Chovanec *et al.*, 2003).

Aquatic ecosystems, including coral reefs and mangrove forests, support fish stocks and maintain water quality. In some instances, ES that support livelihoods can conflict with ES that provide other resilience outcomes. For example, intensive shrimp farming in South East Asia provides the basis of livelihoods for coastal communities, but also leads to deforestation of mangrove forest, thus reducing the resilience of these same communities to natural hazards and eroding the ability of these habitats to support fisheries (Holmlund and Hammer, 1999).

Cultural ES

The ownership of or control or capacity to use biodiversity provides cultural roles in human societies and continues to be important in conferring individual status and position, which in turn can enable or impede income-generating opportunities. For example, those who are endowed with rights and resources to access ES or with the means to use a resource are more likely to exploit livelihoods opportunities (Leach *et al.*, 1999, Fisher *et al.*, 2013).

Institutions and norms have been demonstrated to evolve in a range of cultures closely linked to their environment (Ostrom, 1991, Pretty, 2011); for example, in rangelands (Homewood, 2008), fisheries (Olsson and Folke, 2001) and forest ecosystems (Gibson *et al.*, 2000). Traditional and other current management practices contribute to the sustainable use of ES (MA, 2005). It is often the cultural diversity that arises from different environments that offers high tourism potential (MA, 2005) and there are many examples of communities gaining income from their cultural identity.

On a global level, demand for high-value products, like livestock and fish, is rising in some geographical areas as cultures shift (MA, 2005), which can create new markets or alter existing ones to support livelihoods. Many species of animals and fish offer nature-based recreational value for sport hunting/fishing and associated tourism activities (Holmlund and Hammer, 1999). Species also supply aesthetic value in zoos, aquaria and outdoor areas, including national parks, rivers and urban green spaces. These open spaces hold aesthetic value in terms of their landscapes and habitats, as well as their species assemblages. In the long term, many of these services depend on functioning and resilient ecosystems.

Resilience Outcome 3: Social capital, stability and security

Social capital has been recognized as a key aspect of sustainable livelihoods (Chambers and Conway, 1992) and human resilience (Adger, 2000). The MA identified security (i.e. personal safety, secure resource access) and good social relations (i.e. social cohesion, mutual respect, ability to help others) to be provided as ES (MA, 2005). The processes of improving ecosystem management to build resilience can also help strengthen social ties, particularly through the use of deliberative processes with diverse groups of stakeholders and connecting those of unequal status to challenge collectively the power structures that influence vulnerability (Doswald *et al*., 2014; Aldrich, 2012).

Provisioning ES

Social capital is built through relations of trust, reciprocity, common rules, norms and connectedness through institutions (Pretty and Ward, 2001). Natural resources have long been cooperatively managed via these mechanisms, particularly where ES are limited in time or space (e.g. rangeland grazing or water management (*Ibid.*; Ostrom, 1990)). Thus, in some systems, social capital is required to gain access to ES that support livelihoods.

Declines in ES have been linked to violent conflict. One study suggests that loss or degradation of agricultural land, deforestation, depletion and pollution of freshwater supply, and depletion of fisheries will contribute to social turmoil in coming decades (Homer-Dixon, 1994).

The IPCC Fifth Assessment Report finds food security and human security are closely linked (IPCC, 2014). Urban areas can be particularly susceptible to food price shocks, hunger and poverty (e.g. in 2007-08 cities in more than 20 countries experienced riots in response to rising food prices. Incidentally, the prices of soybean and maize exceed these levels today).

Accessibility to green open spaces in urban areas has been shown to reduce health conditions that can contribute to crime and aggression, thus strengthening communities and security (Elmqvist *et al.*, 2011).

Regulating ES

Regulating ES contribute to provisioning services (e.g. by maintaining soil and climate conditions for agriculture (Butler and Oluoch-Kosura, 2006)), and thus will be critical to meeting food security needs as the global population rises (UNFPA, 2009). Land and water resources must be managed so as to enhance natural and social capital (Boelee, 2013). Regulation of diseases is a service that maintains social order and security, which can easily break down in the event of an epidemic or disease outbreak (Strong, 1999).

There is evidence that currently, and in the past, societies have understood the importance of regulating ES, developing customs and institutions that help maintain biodiversity, water quality and land resources (Berkes, 2003; Folke, 2004). Also, there is substantial evidence of a growing gap between some parts of society that do not sufficiently appreciate and value regulating ES (Butler and Oluoch-Kosura, 2006).

Climate change is an example of this and is increasingly becoming a security problem, due to decreasing access to natural resources that are important to sustaining livelihoods (Barnett and Adger, 2007). Climate change has been recognized as a 'threat multiplier' by the United States military and others (IPCC, 2014; Department of Defense News, 2014). Environmental change can have this effect through impacts on income and social cohesion as institutions break down (*ibid.*).

Cultural ES

While the links between ES and social capital have been described in terms of cultural identity, sense of place, spiritual and amenity value (elsewhere in this paper), there is very little documented on the contribution of cultural ES to the resilience outcomes of social capital, stability and security. The dynamics here are likely to be complex given the relative dearth of literature around cultural ES generally and the complex interactions within the social component of ecosystems.

There is evidence in other bodies of literature that points to relationships. For example, at the global level, natural resource commodity markets can shape geopolitical relationships; for example, China is economically linked to wheat markets in the USA, Argentina and Australia (Naylor, 2008). Urbanization creates shifts in demand and particular types of agricultural production (i.e. intensified commercial production rather than small-scale (Elmqvist *et al.*, 2011)), which then lead to a fundamental change in the composition of societies, forms of social capital and relative stability.

Ecosystems provide significant services in terms of recreation and amenity across the world (MA, 2005). Previous sections have explained how open spaces, landscapes and habitats can contribute to human wellbeing. In addition, use of shared ecosystems for recreation and amenity purposes, such as hiking, fishing, sports and so forth, can also build social capital through increased levels of interaction (Warde *et al*., 2005). In turn, social capital can be built in collective action for sustainable natural resource management (Pretty, 2003).

Many societies continue to define themselves in terms of the spiritual connection to their ecosystems, and to the knowledge that is generated through this (UNEP, 1999). While this is more commonly observed in indigenous communities, these relationships are also seen in urban and industrialized contexts (*ibid.*).

Resilience Outcome 4: Reduced exposure and enhanced adaptive capacity

When managed well, ecosystems can mitigate the impact of many natural hazards including landslides, floods, droughts, wildfire, hurricanes and cyclones. There is growing evidence that ecosystem-based approaches to managing disaster risk and mitigating disaster impacts can make a valuable contribution to human resilience (Sudmeier-Rieux *et al.*, 2006). Similarly, ES are an important factor in shaping the adaptive capacity of communities, particularly those that are poor and dependent on natural resources for their subsistence and livelihoods (Vohland *et al.*, 2012).

Provisioning ES

Productive ecosystems can support sustainable livelihoods and income generation, which are important to human resilience in recovering from disasters (Sudmeier-Rieux *et al.*, 2006). In the longer term, sustainable and strong livelihoods supporting shift from coping with shocks and stresses to adaptation (Adger, 2000); for example, small-scale farmers with additional off-farm sources of income have adapted to shocks that affect crops (disease outbreaks or failed rains) by diversifying their livelihood assets (Ellis, 1999); and pastoralists have increased their resilience to climate variability and drought through diversification of livelihoods (Homewood, 2008). Bundles of ES support diverse food products, increasing resilience to shocks and stresses that differentially affect commodities.

Ecosystems can be a cause of increased disaster risk. For example, the provision of fibre and fuel contribute to wildlife risk and these are services that need to be managed to reduce risk. Wildfire risk fragmentation and climate change interact to increase wildfire risk places in some locations (Hurteau *et al.*, 2013), which will have a greater impact on ES provisioning in systems not previously adapted to fire (e.g. tropical rainforests (Laurence, 2006)). Ecosystems can also increase risk of disease outbreak, through transmission of zoonotic disease through bushmeat consumption, for example (Keesing *et al*., 2010).

The provision of food, water and energy, as well as education and health services, are important for building the adaptive capacity of people whose livelihoods depend on natural resources (Vohland *et al*., 2012). For many communities, especially those living in poverty, access to clean water and wild foods is important for buffering against starvation (Bharucha and Pretty, 2010).

Regulating ES

Ecosystems provide services in terms of reducing disaster risk. Ecosystems can create natural barriers or buffers to extreme events; for example, forests, riverine and littoral vegetation, coral reefs, mangroves, seagrasses, wetlands and dunes. These can mitigate the effects of natural hazards including coastal storms, hurricanes (Costanza and Farley, 2007), surface water flooding, tsunamis, landslides and wild fires. The available evidence for these effects is scarce, although efforts are underway to improve the evidence base, e.g. through the work of Wetlands International and the Science for Nature and People working group on Coastal Defenses. Furthermore, preservation of dynamic habitats in a more natural state also prevents human habitation of these areas, thus reducing exposure to risk.

For example, coral reefs can absorb more than 85% of incoming wave energy, benefitting approximately 200 million people living in low-lying coastal zones around the world (Beck and Shepard, 2012). For example, the matrix structure of the Great Barrier Reef attenuates wave power (Gallop *et al*., 2014) By one estimate, the total net benefit of the world’s coral reefs in terms of coastal protection is US$9 billion annually (Conservation International, 2008). A well-cited example of disaster risk reduction by mangrove forests is the experience of different villages on the same coast in Sri Lanka that were affected by the 2004 Asian tsunami. In one village, Wanduruppa, where mangrove habitats were severely degraded, between 5,000 and 6,000 people were killed, whereas in neighbouring Kapuhenwala, where 200 hectares of mangrove habitat were intact, only 2 deaths were recorded (ProAct Network, 2010).

Similar observations were made on the Indian subcontinent where mangroves and *Casuarina* plantations were shown to attenuate tsunami-induced waves and protect shorelines against damage (Danielson *et al.*, 2005). Cyclone Nargis caused over 135,000 deaths in Myanmar in 2008. The affected area had lost 50% of its mangrove forests since the 1970s (ProAct Network, 2010). Similarly, sand dunes protected one coastal hotel in Sri Lanka’s Yala National Park from tsunami while the adjacent, unprotected property received major damage and almost complete loss of life (Ingram and Khazai, 2012). Examples like this are encouraging governments to invest in ecological restoration to reduce the risk of disasters, including the Philippines, which has pledged PHP 1 billion (approximately US$20 million) for mangrove restoration after Typhoon Haiyan in 2013 (Estrella, 2014). In Vietnam, the Red Cross is investing approximately US$1.1 million planting and protecting 12,000 hectares of mangroves, which is estimated to save around US$7.3 million per year in the cost of maintenance for hard defenses (IFRC, 2002).

However, while vulnerable countries have recognized the importance of ecosystem-based approaches to disaster risk reduction and the evidence base is growing, the appropriateness of such measures needs to be considered alongside, and in combination with, hard engineering solutions (Emily Pidgeon, personal communication).

A similar example from the developed world is the degraded Mississippi deltaic wetlands, which exacerbated the vulnerability of coastal communities to Hurricanes Katrina and Rita (Day *et al.*, 2007). Efforts are now being made by local government and civil society to restore the wetlands to attenuate future hurricane impacts. Floods are one of the most frequently occurring natural hazards and environmental degradation is widely recognized to be an important cause (EM-DAT, 2014). Deforestation rates have been linked to flood frequency at the global level (Bradshaw *et al*., 2005); however, this pattern has not always held up at local scales (FAO & CIFOR, 2005).

Urban green spaces can help to reduce the urban heat island effect, regulate climate through solar absorption and reflection, increase cooling by evaporation and shading, filter dusts and aerosols, improve air quality, regulate wind speeds and store carbon. For example, in 2005 in Washington, D.C., urban vegetation removed 244 tons of carbon dioxide, nitrogen dioxide, particulate matter, sulphur dioxide and ozone, saving an estimated $1.1 million (CBD, 2012). Urban wetland ecosystems can also act as filtration systems for the treatment of sewage and storm water to reduce pollution at the same time as offering amenity value. For example, the wetlands adjacent to Accra, Ghana, act to control flooding and purify water, regulate the city's microclimate and provide food, livelihoods and materials to local people (CBD, 2012).

Because urban areas are characterized by large areas of impermeable surface, large volumes of surface water runoff can pose a risk to populations, particularly under a changing climate. Green spaces and vegetation can mitigate this risk through interception of rainfall and infiltration of surface water in permeable soils. Studies have shown that urban landscapes with 50-90% of impermeable surface area can lose 40-83% of rainfall through runoff, whereas forested landscapes lose only around 13% in similar rainfall events (CBD, 2012).

Ecosystems play a role in sequestering carbon, which assists in migrating against climate change, and regulating diseases, which are responsive to changes in climatic conditions (see previous subsections). The role ecosystems can play in enhancing adaptive capacity to climate change is also gaining attention in the literature (see Box 1). In the context of a changing climate, regulating ES is increasingly important for buffering against extreme events (Vohland *et al*., 2012).

Box 1: Ecosystem-based Adaptation

In recent years, ecosystems have been explicitly recognized as core to addressing climate change and its impacts (Vignola *et al.*, 2009, Uy and Shaw, 2012). Since then, emphasis on the potential of ecosystem-based adaptation (EbA) has grown. A definition of EbA is 'the use of biodiversity and ES to help people adapt to the adverse effects of climate change as part of an overall adaptation strategy' (CBD, 2009, p. 41). This is the definition that has guided much of the research in this area, although there is still some contention around definitions and the concept of EbA (Gretchen Daily, personal communication).

Examples of EbA implementation include rehabilitation of watersheds, promoting agroforestry and conservation agriculture, and creating new markets for income generation and livelihood diversification (Munang *et al.*, 2014). As mentioned previously, some ecosystem types such as forests and veld are important sources of wild foods (Sallu *et al.*, 2009; Barucha and Pretty, 2010). These resources act as important safety nets during drought or crop failure. Much of the literature on EbA is conceptual rather than practical, and while there is work being done by many institutions to implement EbA, including UNEP, IUCN, CI, TNC, WWF and CARE, there has been little progress in defining EbA in practice and this is the focus for future research in this area (Gretchen Daily, personal communication).

EbA interventions are designed to address loss of soil quality or productivity, flooding and erosion, water scarcity and natural hazards. The benefits of these approaches in terms of human resilience include (Doswald *et al.*, 2014):

- Social – improved and secure livelihoods, social cohesion and community, new or preserved recreation areas, better quality land for agriculture/livestock, better water security and protection from loss and damage;
- Environmental – biodiversity conservation, carbon sequestration and mitigation benefits, land erosion and degradation prevention, habitat creation and restoration, and mitigation of microclimate variability;
- Economic – damage costs prevented, new or improved income, profits, savings compared to alternative adaptation approaches, and income from subsidies.

However, there is limited evidence of implementation of EbA in certain ecosystems, including grasslands/savannahs, mountain and marine biomes. The definitions and terminology around EbA also hinder the search for evidence, with interventions often not labelled as EbA per se. There is a lack of quantitative measures of EbA, which makes it difficult to provide evidence to policymakers (Doswald *et al*., 2014).

Cultural ES

In most cases, perceptions and responses to climate or disaster risk are partially influenced by social and cultural factors (IPCC, 2014, IFRC, 2014). An example of how beliefs shape attitudes to risk is Pacific Island settlement patterns. In the past, inhabitants built their homes inland and at altitude due to their experience of tsunamis and other coastal hazards. After the arrival of European missionaries, these communities' belief structures began to shift, and they moved down to coastal areas to benefit from trade and coastal development opportunities (IFRC, 2014).

Cultural factors and TEK can determine where people settle and how they manage resources, based on experience of risk factors. The IPCC finds with medium confidence that loss of transmission of TEK, substitution of traditional livelihoods, and promotion of sedenterization will limit climate change in many regions (IPCC, 2014, Nakashima *et al*., 2012). On the other hand, sense of place and cultural identity can also be a barrier to action (Adger, 2013, Fresque-Baxter and Armitage, 2012); for example, constraining migration away from areas of high exposure (Foresight, 2011).

TEK has developed to cope with climate hazards to food security and livelihoods (IPCC, 2014, Chapter 7). For instance, weather forecasting and crop diversity have been useful strategies for Sahel agropastoralists and there are numerous such examples in the literature. Furthermore, cultural preferences for particular breeds, wild foods or crops can reduce vulnerability to shocks and stresses; for example, Maasai preferences for drought-resistant Zebu cattle (Carabine, 2014) and San preferences for veld foods in times of stress (Sallu *et al.*, 2009).

Part Two: How do we measure the value of ecosystems in building resilience?

Framing the argument

Linking ecosystems and resilience

As discussed in the previous section, frameworks that link ES and human resilience are still nascent. Nonetheless, the literature does make clear linkages between ES and human resilience in terms of basic needs, livelihoods, social capital and reducing exposure to risk. In this section, we look at the evidence around how to measure the value of ecosystems in building resilience.

It is nearly impossible to say that X intervention resulted in X increase in resilience. Resilience is not static in time, and multiple factors affect human resilience, some working to improve it and some working to detract from it. Without clarity and agreement around what defines human resilience and how you measure it, the task of identifying and measuring changes in human resilience is even harder.

However, when we consider the resilience dividend produced by investment in ES as linked to specific resilience outcomes (as defined in Figure 1), the evidence is more abundant. While studies may not explicitly identify linkages between ES and resilience, many do consider the role of ES in contributing to basic needs, health and wellbeing; livelihoods; social capital, stability and security; reduced exposure or enhanced adaptive capacity; or reduced avoided losses.

There is a large literature on valuing ecosystems more generally. Ecosystems are typically valued using methodologies to establish 'use' and 'non-use' values. Use values are typically monetization of human use of ecosystems, or ES, and this is where this review focuses. Non-use methodologies use economic approaches to value the existence value of a natural resource. As such, while the existence of an ecosystem (outside of its use value) clearly is important to human wellbeing, it pertains less to human outcomes and hence is not reviewed as part of this report.

This section begins by highlighting several global initiatives that are seeking to add evidence to this discussion. This is followed by a discussion around the literature.

Global initiatives

While there are many initiatives that seek to value ecosystems, this rapid review highlighted two initiatives that are focused specifically on valuing ecosystems in relation to their benefit for human wellbeing. Both of these initiatives offer potential frameworks for continuing to develop this area.

The Economics of Ecosystems and Biodiversity (TEEB) is a global initiative focused on drawing attention to the economic benefits of biodiversity, including the growing cost of biodiversity loss and ecosystem degradation. Many of the resources on its website are focused specifically on the economics of ES for human outcomes.

There is also TEEB guidance for country-level studies that focus on evaluating national policy priorities in terms of their ecosystem service dependencies and impacts, identifying and valuing important ES and natural areas that deliver them, and proposing changes in policies and mechanisms that address national priorities and ecosystem service losses. As such, the guidance is very much focused on measuring the value of ecosystems in delivering human outcomes.

The Natural Capital Project InVEST model is a free and open source software that quantifies, maps, and values the goods and services from nature that contribute to sustaining and fulfilling human life, and as such explicitly seeks to measure the value of ecosystems for human outcomes. InVEST's modular toolset enables users to quantify, visualize and compare the delivery of key ES under different scenarios of land, water, and marine uses. Outputs describe natural resources in terms of their biophysical supply, the service they provide humans, or their projected socioeconomic value.

Both interviews with key informants and literature review found that there is very little that makes the link between the value of ecosystems and human resilience. There is a greater body of literature that attempts to value or measure ecosystems and human outcomes.

Key literature

The literature around ES and human outcomes seems to address the question of links between the two largely from two perspectives:

1. What is the value of X ecosystem service to X human outcome? (E.g. what is the value of forests to human income?)

2. What is the cost of X ecosystem service to achieve X human outcome as compared with other traditional technological services approaches? (E.g. cost per avoided loss of a sea wall as compared with a mangrove).

3. A third perspective that seems to have little evidence, but which would be quite compelling, is: What is the loss of investment that will result if ES are not integrated into wider resilience planning? Or, in other words, if we do not invest in ES, what will happen to the value of existing investment in wider development initiatives?

These questions are addressed in the following sections 2.1, 2.2 and 2.3, respectively.

2.1. What is the value of X ecosystem service to X human outcome?

Overview

The vast majority of the literature reviewed is very context specific, using case studies to link a specific ecosystem service to a specific human outcome.

Perhaps the key finding from the literature, and in particular a study by De Groot *et al.* (2013), is that the vast majority of ES projects have benefits that outweigh the costs, and therefore warrant investment. Furthermore, investments in activities that improve incomes are very likely to result in helping people to rebound more easily from a crisis, as income and assets (both amount and diversity) are key determining factors of resilience (UNDP, 2014).

It is also clear from this literature that there are some very robust examples of the ways in which ES can have tangible impacts on human outcomes, in terms of lessening the impact of disaster events (e.g. reduced exposure in the Dominican Republic and flood protection in Fiji).

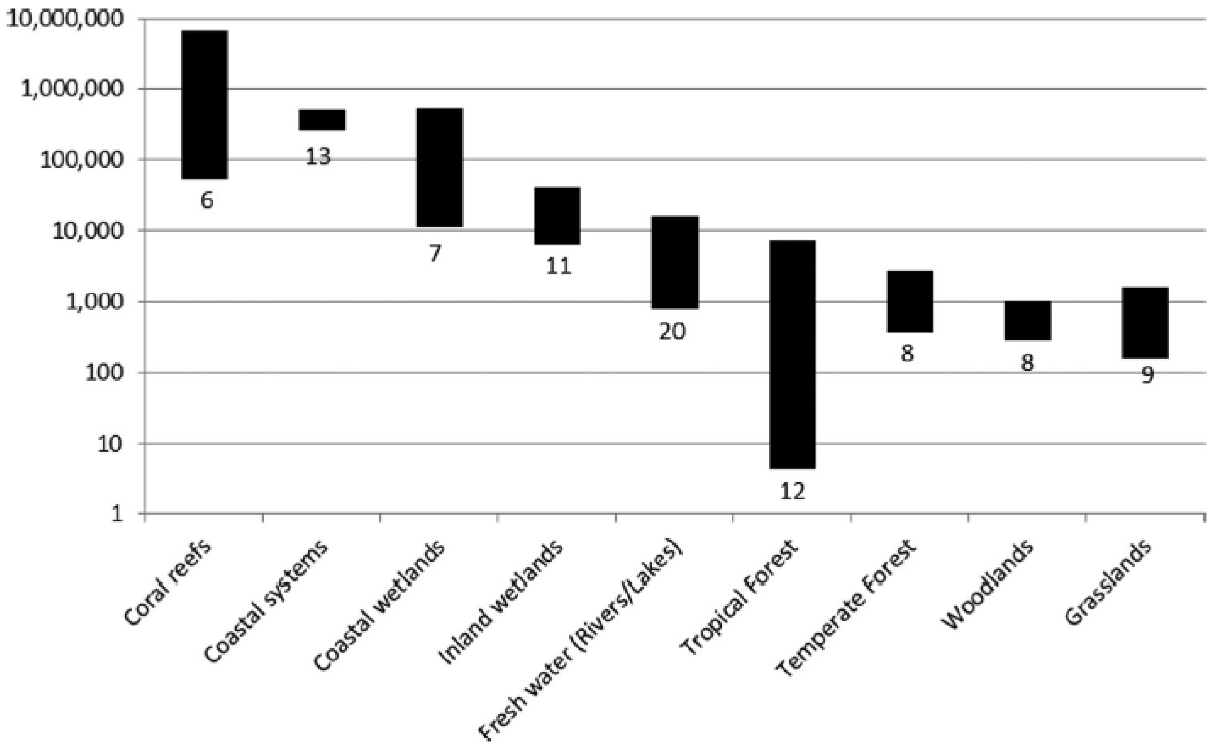
Examples from the literature

After screening over 200 studies, De Groot *et al.* (2013) examined the costs (94 studies) and benefits (225 studies) of ecosystem restoration projects that had sufficient reliable data in 9 different biomes, ranging from coral reefs to tropical forests. Costs included capital investment and maintenance of the restoration project, and benefits were based on the monetary value of the total bundle of ES provided by the restored ecosystem. Benefit-cost ratios ranged from about 0.05:1 (coral reefs and coastal systems, worst-case scenario) to as much as 35:1 (grasslands, best-case scenario).

The results provide only partial estimates of benefits at one point in time, and reflect the lower limit of the welfare benefits of ecosystem restoration because both scarcity of and demand for ES is increasing and new benefits of natural ecosystems and biological diversity are being discovered. Nonetheless, when accounting for even the incomplete range of known benefits through the use of static estimates that fail to capture rising values, the majority of the restoration projects analysed provided net benefits and should be considered not only as profitable but also as high-yielding investments.

The study finds that coastal systems and wetlands typically have the highest restoration costs per hectare, whereas forests, woodlands and grasslands tend to have lower costs per hectare. (See Figure 2 below).

Figure 2: Range of ecosystem restoration costs (log cost in 2007 US$/ha) of 9 major biomes. Numbers below bars represent the number of case studies of each biome.



The study also assesses the mean total economic value (TEV) of each biome, based on the sum of the monetary values of 22 ES. Coral reefs and coastal areas had among the highest natural capital benefit values (Table 2), but these systems had the lowest internal rates of return and benefit-cost ratios of all the restored ecosystem types due to high restoration costs. In contrast, grasslands and woodlands had relatively low asset values (Table 2), but internal rates of return were 20–60% and benefit to cost ratios were up to 35; thus, they offered very high returns on investment.

Table 2: Total economic value (TEV) of 10 biomes in 2007

			Discounted value (US$/ha at 75% TEV[a]	
	No. of estimates	Mean TEV of all services in US$/ha/year (standard deviation in brackets)	Social Discount Rate = 2%	Social Discount Rate = 8%
Open oceans	14	491 (762)	9,167	3,616
Coral reefs	94	352,915 (668,639)	6,589,166	2,598,729
Coastal systems	28	28,917 (5,045)	539,900	212,934
Coastal wetlands	139	193,845 (384,192)	3,619,220	1,427,399
Inland wetlands	168	25,682 (36,585)	479,501	189,112
Rivers and lakes	15	4,267 (2,771)	79,668	31,421
Tropical forest	96	5,264 (6.526)	98,283	38,762
Temperate forest	58	3,013 (5,437)	56,255	22,187
Woodlands	21	1,588 (317)	29,649	11,693
Grasslands	32	2,871 (386)	53,604	21,141

[a] *over 20 years*
Adapted from De Groot et al. (2010).

Overall, the study found that the restored ecosystems that offered the most value for restoration investment in absolute terms (i.e. based on net present values) were coastal wetlands and inland wetlands, followed by tropical forests.

There are a variety of case studies that highlight how a specific ES can contribute to a specific human outcome. Table 3 presents summaries of some of these studies, to give some examples of the kinds of outcomes that are documented and monetized. Many of the examples reviewed here relate to livelihoods and reduced exposure as two key categories of human resilience. The other two categories – basic needs, and social capital, were less well represented in the literature, as is the contribution of ES in enhancing adaptive capacity. Basic needs – mainly access to water – is covered much more heavily in the next section that reviews ES and human measures to achieve a given outcome.

Table 3: Case study examples quantifying resilience outcomes

Ecosystem service	Resilience outcome	Summary
Forest provisioning	Livelihoods	The study estimated the annual per hectare average values of provisioning services for Cameroon's forests at US$560 for timber, US$61 for fuelwood and US$41-70 for non-timber forest products (Lescuyer, 2007).
Forests	Reduced exposure	Estimated the value of flood protection by tropical forests in Cameroon at US$24 per hectare per year (Yaron, 2001).
Forests	Livelihoods	Estimated the average value of pollination services provided by forests in Sulawesi, Indonesia, at €46 euros per hectare. As a result of ongoing forest conversion, pollination services are expected to decline continuously and directly reduce coffee yields by up to 18% and net revenues per hectare up to 14% within the next two decades (Priess *et al*., 2007).
Forests	Reduced exposure	By 2004 only 3.8% of Haiti was under forest cover compared to 28.4% of the Dominican Republic (DR). Floods and Hurricane Jeanne killed approximately 5,400 people in Haiti due to a loss of green cover, destruction of storm-protecting mangroves and a loss of soil-stabilising vegetation, causing landslides that led to most casualties. In DR, which is much greener and still has 69,600 hectares of mangroves, Jeanne claimed less than 20 lives (Peduzzi, 2005).
Protected wetlands	Livelihoods	In Venezuela, it is estimated that the national protected area system prevents sedimentation that would reduce farm earnings by around US$3.5 million/year (Pabon, 2009).
Tropical Forests	Basic needs, health and wellbeing	The indirect watershed benefits of tropical forests in the Ko'olau watershed, Hawaii, were valued using shadow prices. The net present value of the contribution to groundwater recharge of the 40,000 hectare watershed was estimated at between US$1.42 billion and US$2.63 billion (Kaiser and Roumasset, 2002).
Mangrove restoration	Reduced exposure; livelihoods	An economic analysis in the Nam Dinh Province of Vietnam suggested that restoring mangroves would cost US$166 per hectare in planting, capital and maintenance, but would provide benefits totalling US$630 per hectare. These benefits included not only the avoided costs of sea dyke upkeep, but also the livelihood co-benefits of timber and honey provisioning and fish-stock maintenance (Tri *et al*., 1998).
Floodplain restoration	Livelihoods	A study calculated that restoration of the Skjern River floodplain in Denmark would cost US$44.2 million but provide net present benefits of US$2.3 million in avoided water pumping (at present used to prevent flooding) and US$84.6 million in co-benefits, including hunting, fishing, recreational opportunities and biodiversity conservation (Dubgaard, 2004).

2.2 What is the cost of X ecosystem service to achieve X human outcome as compared with other technological approaches?

Overview

While the above studies are very useful for helping to place a value on ES and their contribution to human outcomes, and mostly demonstrate that return is greater than the investment, such an approach does not give the kind of comparative analysis that allows for prioritization of ecosystems approaches above others. For example, an ecosystem service may lead to a 10% increase in income, but that does not mean that it is the most cost-effective way of generating an increase in income.

A number of studies have undertaken comparative analyses between EbA and more traditional approaches. Some make the case very clearly for EbA as opposed to a more traditional approach. However, some also highlight the various trade-offs between ES, traditional/hard engineering approaches, and 'hybrids' that combine the two.

A variety of examples from the literature are highlighted here. These are divided by category, namely freshwater systems, coastal planning/protection, food security and hybrid measures.

Freshwater systems

A number of studies were found that compare different approaches for protecting and ensuring clear water supply. Each of these studies specifically compares an ecosystem approach for protecting water with more traditional water filtration systems.

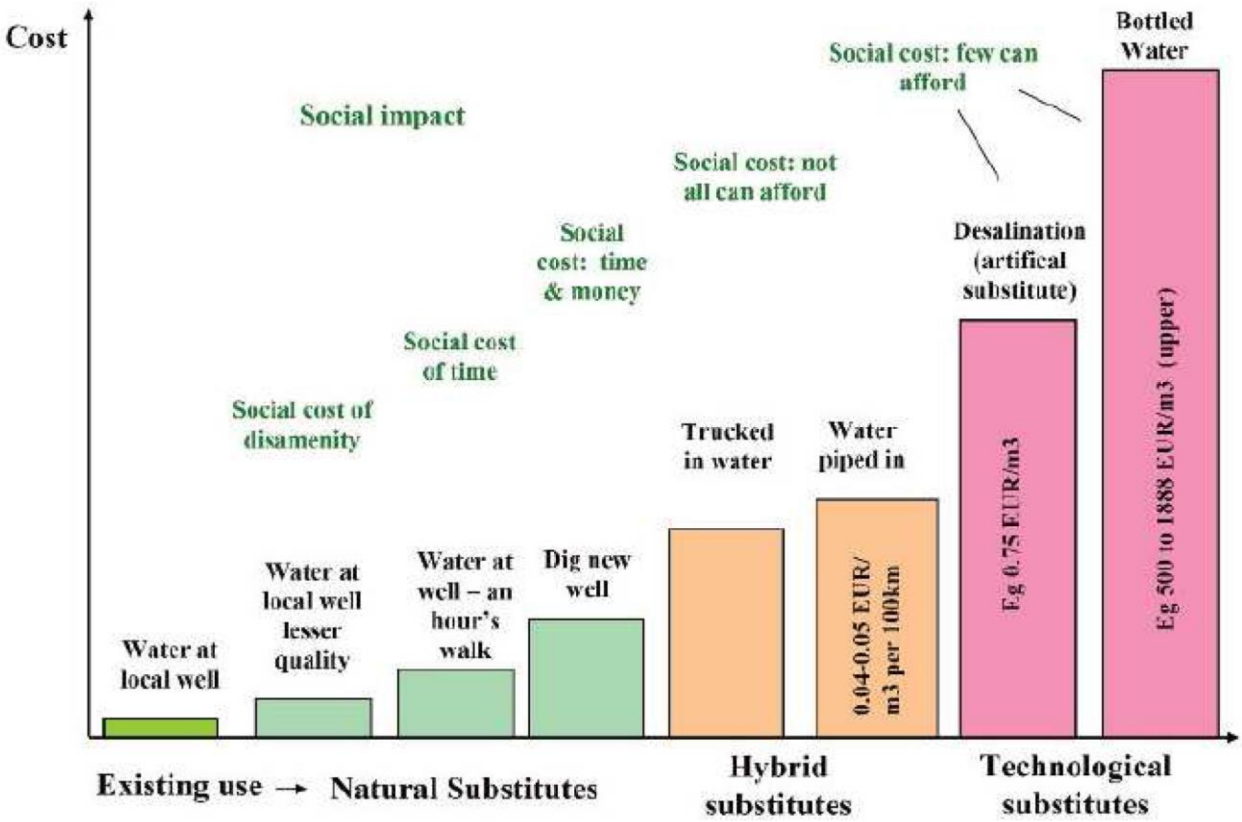
- *Water supply in New York:* about 9 million New York City residents receive 1.3 billion gallons of water per day, or 90% of their water, from the Catskill-Delaware watershed. Protection of the watershed has cost the city US$150 million per year over the past 10 years. The cost of a water filtration plant sufficient to filter water for New York City would have been US$6 billion-8 billion up front and would have operating costs of US$300 million per year (Postel and Thompson, 2005).

- *Water supply in Columbia:* the Paramo wetland ecosystem above Bogota, Colombia, filters out contaminants and traps sediment so efficiently that the water it delivers to the city's treatment plant only needs chlorine treatment for disinfection. This service saves US$ 19.6 million in avoided water filtration facilities. The cost of building the water reservoir that will store water until the year 2032 to supply the Bucaramanga, Giron and Floridablanca municipalities in Colombia is estimated at US$127 million (Jones *et al.*, 2012).

- *Water supply in New Zealand:* in Te Papanui catchment, the central Otago conservation area is contributing to Dunedin's water supply, saving the city US$ 72 million (New Zealand Department of Conservation, 2006).

Figure 3 provides an excellent demonstration of the trade-off potential for water supply, demonstrating the relative cost of different approaches, both ES and technological (TEEB, 2009). It demonstrates how more traditional EbA is are typically much lower cost, followed by hybrid solutions, and then technological substitutes that are typically very high cost.

Figure 3: Substitution potential for ecosystem services



Source: TEEB 2009 (after ten Brink et al. 2009)

Coastal planning/protection

A variety of studies quantify the contribution that various measures, both ecosystem-based as well as hard structural measures, can make to coastal planning and protection.

Perhaps the most comprehensive study evaluated a range of flood risk mitigation measures for Fiji (Brown *et al.*, no date), including planting riparian buffers, afforesting the upper catchment, and planting floodplain vegetation. For hard approaches, these mitigation options include reinforcing riverbanks, dredging rivers and raising houses. The study also evaluates an integrated approach to adaptation that includes both EbA and hard options to assess the robustness of the findings. The findings showcase how the economic case for EbA really arises from a combination of both direct benefits (e.g. protection), as well as the additional benefits that arise from ES associated with the measure. A summary of the findings follows:

- Although planting along streams and riverbanks does not provide the highest level of protection from flooding, the low cost of implementation coupled with the ES such as carbon sequestration, non-timber forest products, and habitat provision means that riparian planting has the highest impact per dollar spent on mitigation (i.e. it is the most efficient);

- Upland afforestation provides the greatest benefits overall, because trees not only reduce damage from flooding, but also produce large quantities of monetized ES, such as fruits, firewood and carbon sequestration. Afforestation can also provide benefits that were not monetized in this study, including habitat provision and erosion control. However, the cost of planting and monitoring large areas is relatively high, rendering upland afforestation less efficient than riparian planting;

- The benefits of planting native vegetation exceed the costs when climate change is expected to be moderate or severe, and the opportunity costs to planting in areas previously used for agriculture are modest. However, planting native vegetation in floodplains is neither as efficient as riparian buffers nor as effective as upland afforestation, so should be considered only as part of a mixed adaptation strategy;

- The benefits of river dredging exceed the costs under the moderate and extreme climate change scenarios. However, the repeated cost of dredging the river at least once every 10 years is high relative to the benefits, particularly in the Ba River catchment. In the Penang River catchment, river dredging is more efficient than afforestation and floodplain planting, although it trails behind riparian buffers in terms of efficiency. Importantly, dredging does not reduce the flood risk in communities in the upper catchment (i.e. the benefits of dredging accrue exclusively downstream, which may or may not be desirable);

- Neither reinforcing riverbanks nor raising houses is economically viable. In fact, under most scenarios, the costs of these activities greatly exceed their benefits; and

- A mixed intervention that incorporates both hard and EbA approaches is effective under most scenarios, indicating that it may be preferable to many approaches. This would particularly be the case if this approach incorporated a number of 'single-focus' options with positive NPVs (e.g. riparian planting, afforestation, and dredging). Nevertheless, we note that the cost of hard approaches can be high, and hence the efficiency of mixed interventions is lower than that of some EbA by themselves.

A study by Jones *et al.* (2012) amalgamated data from numerous studies to compare ecosystem-based approaches with hard-engineering options. Table 4 includes several of these comparisons.

Table 4: Cost comparison of Ecosystem-based Adaptation and hard engineering options

Ecosystem-based approaches	Hard-engineering options
A study in the Caribbean looked at the value of coral reefs as a natural buffer that provides protection against erosion and wave damage. In the Turks and Caicos Islands, this protection is valued at US$16.9 million per year.	The cost of using hard-engineering options (dykes and levees) for coastal protection in the Turks and Caicos Islands has been estimated at 8% of GDP, or US$223 million.
In the USA, the wetlands of the Mississippi Delta are valuable ecosystems providing services worth US$12 billion–47 billion per year. If the wetlands of New Orleans were to be restored and used as part of the coastal defense system, the estimated cost would be: for marshland stabilization US$2 per square meter; for marshland creation US$4.30 per square meter; and for freshwater diversion US$14.3 million.	The cost of engineering solutions for coastal defense in New Orleans is high. To heighten a dyke by 1 m costs between US$7 million and US$8 million per kilometre. To heighten concrete floodwalls costs between US$5.3 million and 6.4 million per kilometre length. To heighten closure dams (in water) 1 m costs US$5.3 million per kilometre. To armor levees for each square meter costs between US$21 and US$28.
In the Maldives, coral reefs and other coastal ecosystems provide critical protection to coastal communities from storms and erosion, substantially reducing storm-related damage and saving lives. Conserving the reefs to prevent their ongoing degradation as a result of pressures ranging from overfishing to coral mining, through establishment of marine protected areas, would cost approximately US$34 million in start-up and approximately US$47 million annually (scaled up from calculations for a smaller protected area in the	If the reefs were lost, the cost of building hard infrastructure such as seawalls, breakwaters and other forms of coastal protection to replace the natural reefs has been estimated at US$1.6 billion–2.7 billion.

Maldives), would maintain their critical protection service and could generate ~US$10 billion per year in co-benefits through tourism and sustainable fisheries.

Following a slightly different approach, a study of mangrove restoration in Vietnam compared forest restoration with aquaculture development as an alternative use of the coastal space. The study found that mangrove forest restoration generates larger benefits than that of aquaculture: about VN$21 billion compared to VN$10 billion over 22 years. The benefits of mangrove restoration are approximately double that of aquaculture development (Tuan and Tinh, 2013).

Food security

A couple of studies used a comparative cost effectiveness analysis to assess ES approaches as compared with more traditional agricultural measures. As stated before, these are just a few examples to highlight the types of evidence out there, and there are undoubtedly numerous more.

A study in Malawi assessed the use of land management practices as compared with fertilisers. The use of sustainable land-management practices such as agroforestry (using trees and shrubs in pastures and croplands) can increase farmers' resilience to climate change through sustaining or increasing food production. By intercropping maize with a nitrogen-fixing tree, *Gliricidia sepium*, Malawi farmers increased average yields fourfold, at minimal cost. To increase average yields fourfold by using nitrogen-based inorganic fertilizers would cost Malawi farmers US$11.6 million annually (Scherr and Sthapit, 2009).

A similar example compares land management practices with irrigation. In Roslagen, Sweden, smallholder farmers have developed ecosystem-based practices to buffer against climatic variability such as diversifying crops among fields, intercropping and crop rotations, and using multiple sowing dates to maintain a diversity of crops that are more likely to survive in an uncertain climate. They also use crops or trees for shade to conserve moisture, and forest or tree protection to preserve groundwater sources, all at negligible direct cost. By contrast, much of Europe uses forms of micro-irrigation or drip irrigation to cope with drought. Micro-irrigation can increase conventional irrigation water use efficiency from 20-30% to 90%. The average cost for micro-irrigation ranges from US$416 to US$950 per hectare (Jones *et al.*, 2012).

Hybrid measures

Arkema *et al.*: Recent calls for ocean planning envision informed management of social and ecological systems to sustain delivery of ES to people. But until now, no coastal and marine planning process has applied an ES framework to understand how human activities affect the flow of benefits, to create scenarios and to design a management plan. This study developed models that quantify services provided by corals, mangroves and seagrasses. The results suggest that the preferred plan, which combines conservation and development goals, will lead to greater returns from coastal protection and tourism than outcomes from scenarios oriented towards achieving one or the other. The final version of the preferred plan improved expected coastal protection by over 25% and more than doubled the revenue from fishing compared to earlier versions, and including outcomes in terms of ecosystem service supply and value allowed for explicit consideration of multiple benefits from oceans and coasts that typically are evaluated separately in management decisions.

Goldstein: This study quantified ecosystem service values to help the largest private landowner in Hawaii, Kamehameha Schools, design a land use development plan that balances multiple private and public values on its North Shore land holdings. The study used the InVEST software tool to evaluate the environmental and financial implications of seven planning scenarios, encompassing contrasting land use combinations, including biofuel feedstocks, food crops, forestry, livestock, and residential development. All scenarios had positive financial returns relative to the status quo of negative returns. However, trade-offs existed between carbon storage and water quality, as well as between environmental improvement and financial return. Based on this analysis and community input, Kamehameha Schools is implementing a plan to support diversified agriculture and forestry. This plan generates a positive financial return ($10.9 million) and improved carbon storage (0.5% increase relative to status quo) with negative relative effects on water quality (15.4% increase in potential nitrogen export relative to status quo). The effects on water quality could be mitigated partially (reduced to a 4.9% increase in potential nitrogen export) by establishing vegetation buffers on agricultural fields.

2.3 What is the loss (of investment) that will result if ecosystem services are not mainstreamed into wider resilience planning?

To put this question another way, if we do not invest in ES, what will happen to the value of existing investment in wider development initiatives? This type of framework has been used heavily in the DRR and CCA fields, demonstrating the losses that can be avoided by mainstreaming DRR and CCA into wider development planning.

GDP of the poor

One of the more comprehensive and universal measures of the value of ecosystems to human outcomes is the 'GDP of the poor' analysis presented in the TEEB studies. This analysis is particularly relevant because efforts to improve human resilience intrinsically focus on the poorest.

An important finding of many studies reviewed in a study by TEEB is the contribution of forests and other ecosystems to the livelihoods of poor rural households, and therefore the significant potential for conservation efforts to contribute to poverty reduction (TEEB, 2010). For example, it has been estimated that ES and other non-marketed goods account for between 47% and 89% of the so-called 'GDP of the poor' (i.e. the effective GDP or total source of livelihood of rural and forest-dwelling poor households), whereas in national GDP agriculture, forestry and fisheries account for only 6% to 17% (*ibid.*).

It therefore follows that, if we do not mainstream ES into our wider development work, we put at risk at least half of the GDP of the poor, undermining all other efforts at poverty reduction.

A GDP of the poor analysis was recently used for Indonesia (Ministry of National Development Planning, 2014), as part of Indonesia's Green Economy Model (I-GEM), to help evaluate the trade-offs and test the sustainability dimensions of policy interventions. The model estimated the percentage of income from ES in Central Kalimantan Province, for villages representing four different types of income dependencies (forest, riverside, rural mixed with rattan, rural mixed with coal), with average ecosystem-based cash and non-cash income representing between 34% and 86% of total income.

The findings clearly indicate the relative contribution that ES make to income (as a key measure of household resilience), and had strong policy implications. For example, the model showed that even slight improvements in forest cover are important for the province's economy, as positive effects are seen in terms of reduction in emissions, increases in household incomes and more jobs created by the green sector. For local planners who face the challenge of siding with development or preservation, the model presents a strong and clear indication of where complementarities between the two exist and where investments should be targeted to result in dual benefits.

Limitations to measuring ES

Measuring the value and contribution of ecosystem services can play a key role in helping a wide range of stakeholders to understand and commit to ensuring the protection and restoration of ecosystems, especially when these services are linked to human outcomes. However, there are also several important limitations to measuring ES that must be considered carefully when reviewing or undertaking such analysis.

There are a number of characteristics of ES that can make valuation of their benefits, as compared with more traditional measures, misleading.

- *Time:* The benefits of ES can be realized over a longer time frame. As a result, economic analysis can weigh traditional measures as more cost effective if the benefits are only assessed over a short time frame. For instance, if you look at fertilizers versus soil and water conservation (SWC) practices over a few years, fertilizers might be most cost effective because they will have very high yields. However, if you look over 20 years, the SWC is more likely to be cost effective. In other words, current use versus future resilience can play a key role in how different measures are weighed up.

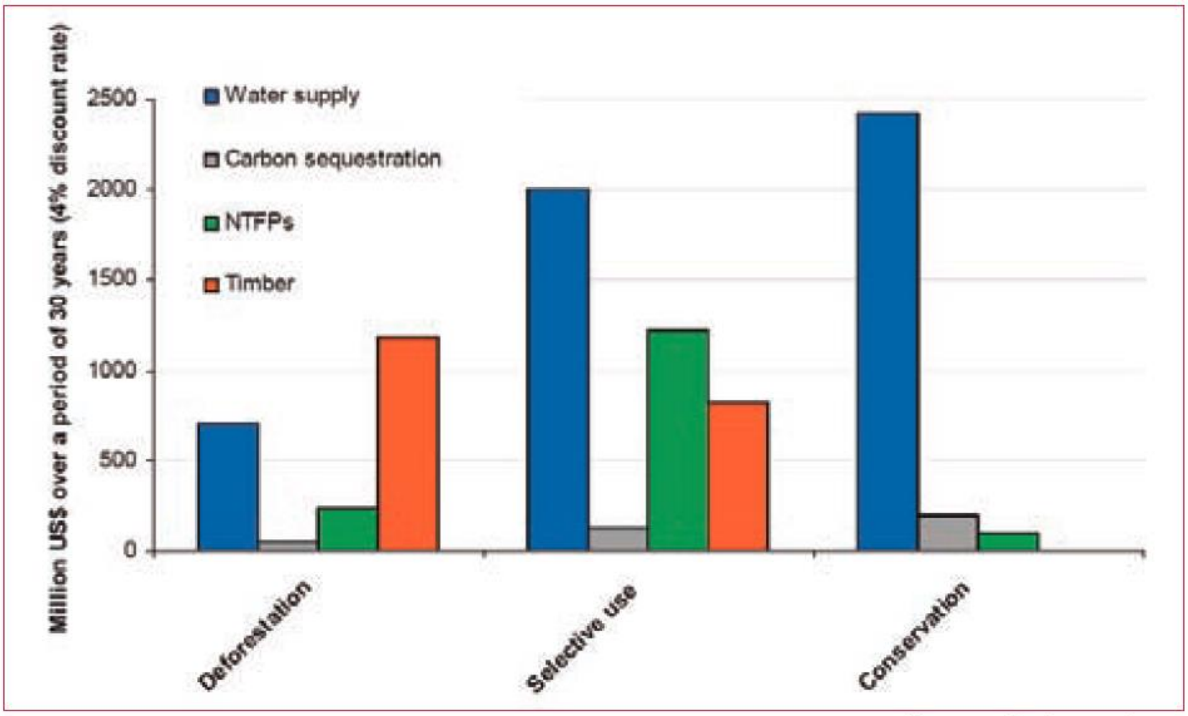
- *Uncertainty:* There is a great deal of uncertainty over what ES we will need in the future, how climate change will affect ES and the economies dependent on them, etc. We are making decisions with incomplete information. As a result, using the best information available, a valuation of ES may lead to poor decision making. Any attempts to value ES much use a conservative and precautionary approach to ensure that decision making is based not only on current information but also future scenarios.

- *Distribution of benefits:* While an ES may produce net benefits, there will often be differentiation between who receives those benefits. The following two figures show how ES can result in positive human outcomes for one sector, or one group of people, but not for another (source: TEEB, 2010). The poor and marginalized are not always the ones to receive benefits from ES, even though their livelihoods are so highly dependent on them. It is critical to understand the distribution of benefits when measuring the human outcomes of ES.

- *ES can often deliver a range of co-benefits* – additional benefits that were not directly intended as a result of the project. And these benefits can be significant. A key strength of economic valuation techniques such as Cost Benefit Analysis is that these benefits can be captured; however, this is not always done systematically in analyses and can lead to lack of comparability across projects or an undervaluation of benefits. Along similar lines, the replacement value of replacing an ES that has been removed can be very high as compared with protecting it in the first place, and this difference in values is not always incorporated. This can also be a key strength of economic valuation techniques if these factors are considered in full.

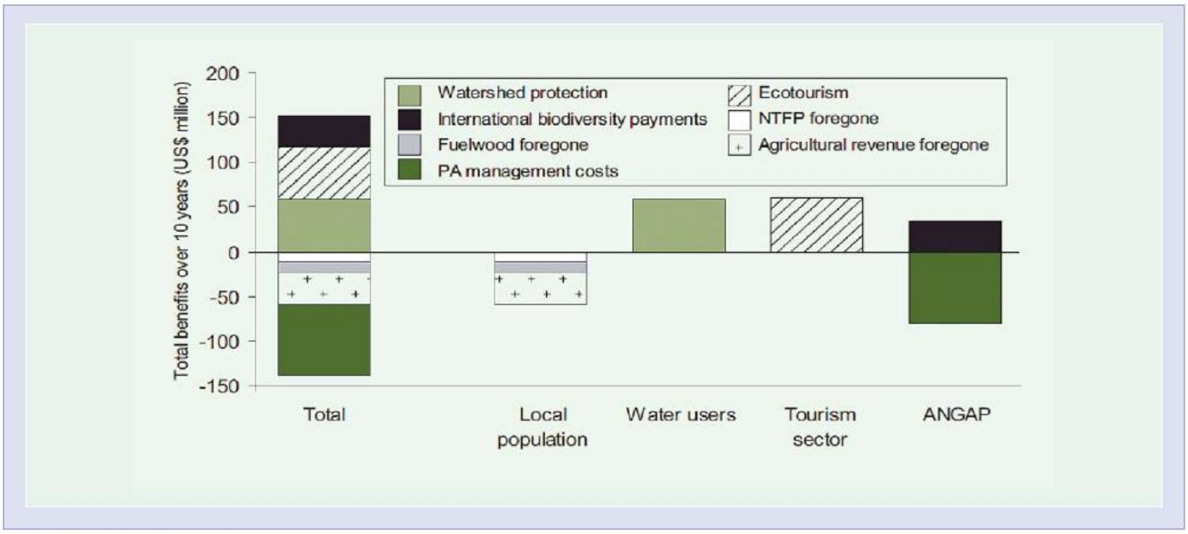
- *Hard infrastructure can often have higher protection levels than natural infrastructure.* However, when it fails (for example a sea wall collapses in a storm), it often fails catastrophically, resulting in significant damage and losses. Hard infrastructure is typically threshold dependent. In other words a sea wall may be built to a height that is sufficient for most flood events. But if the maximum threshold is exceeded, the damage can be significantly higher, especially as populations may be more likely to build in vulnerable locations with a false sense of security.

Figure 4: Value of selected provisioning and regulating ecosystem services under different land use scenarios in the Leuser National Park, Indonesia



Source: van Beukering et al. 2003

Figure 5: Distribution of the costs and benefits of Madagascar's protected areas



Source: Pagiola 2004, p. 24

"More productive" does not necessarily equate to "more resilient". ES can result in a myriad of benefits, but many of these can only be evaluated qualitatively. The benefits that we can measure quantitatively are typically outcomes such as improved income, education and health. However, this can be misleading by suggesting that increases in income and assets signal a more resilient household. Whilst productivity certainly plays a key role, resilience requires more systemic rather than linear thinking, and this is not necessarily reflected in such analysis.

Decision-making will ultimately depend on a range of factors. Valuation of ES are critical to making the case for greater investment in restoration and protection. However, any valuation analysis must never be taken in isolation and must be understood within the context of the wider political economy.

Conclusions and knowledge gaps

Evidence linking ES to human resilience is relatively scarce in the literature. The links between ES and human wellbeing have been fairly well established in the literature. In practice, these have not been well elucidated. The relationship between ecosystems and human resilience has been less well explored, and such conceptual work is still in its early stages. This review presents examples from the literature that support the argument that provisioning, regulating and cultural ES contribute to human resilience in terms of basic needs, wellbeing, livelihoods, social capital and reducing exposure to risk and enhancing adaptive capacity. However, knowledge gaps remain about the role of different ES in determining different resilience outcomes in different contexts. For example, less is known about the role ES play generally in urban small-scale agricultural systems compared to forests or coastal systems.

Emerging from the ES literature are efforts to conceptualize ES as bundles, rather than singular flows that can address multiple objectives if considered in a systemic way (Bennett *et al.*, 2009). Such approaches will help to clarify the trade-offs, scales of provision and inherent uncertainty and dynamism that characterize ES flows, as well as the links with resilience (Mace *et al*., 2012). However, there is still an urgent need for theoretical understandings of relationships, drivers and interactions among ES themselves. Furthermore, we need to develop much better understandings of complex social-ecological systems to inform policy and planning for management of ES (Carpenter *et al.*, 2001). Such work is still not sufficiently interdisciplinary.

There is a strong economic case for investing in ES. The vast majority of studies find that the costs of ecosystem restoration and protection are far outweighed by the benefits. Perhaps the most systematic analysis is a 2013 study by De Groot *et al.* that evaluates 200 economic assessments. It is clear that many ecosystem projects can both: 1) lessen the impacts of extreme events (e.g. coastal flooding and landslides); and 2) provide additional benefits to household economies through ES and income generation that help families to rebound by contributing to household income and assets. In fact, the ability of ES to both avoid losses and provide benefits significantly strengthens the economic case for ES.

The relative contribution of ES to human outcomes is much harder to assess. Clearly, many interventions contribute to human outcomes, and often work best when implemented together to create holistic programming. It is very hard to differentiate how much ES contribute to a specific outcome. A forestry study by Bradshaw et al. 2005 was the only study found in this review that assesses the degree to which ES contributed to flood risk (and hence human outcomes). The study uses data from across 56 countries to build a model that demonstrated that flood frequency is negatively correlated with the amount of remaining natural forest and positively correlated with natural forest area loss. Based on an arbitrary decrease in natural forest area of 10%, the model-averaged prediction of flood frequency increased between 4% and 28% among the countries modelled. Using the same hypothetical decline in natural forest area resulted in a 4-8% increase in total flood duration.

The findings from De Groot *et al.* suggest that the ecosystems that offer the most value for restoration investment in absolute terms (i.e. based on net present values) are coastal wetlands and inland wetlands, followed by tropical forests. While there are variation within this, based on the average costs and the average benefits from their review of several hundred studies, these three ecosystems have the greatest potential. Furthermore, wherever ecosystem restoration projects can be designed to bring about both protection as well as development gains, the economic argument will be strengthened.

There is a strong argument for mainstreaming ES into any attempts to build resilience; however, very few studies assess this from a practical perspective. The DRR and CCA agendas very successfully created an argument for integrating risk into development agendas, by screening development portfolios and quantifying how much development spending was at risk if these issues were not taken into account. A similar argument could be made for ES; for example, if the government plans to invest heavily in water infrastructure, but due to a lack of ecosystem planning groundwater resources will be insufficient or lacking quality, the value of that investment becomes a loss.

The picture becomes even more complex when we recognize the characteristics required for resilience outcomes. When considering what resilience actually means in terms of processes, difficulties can arise in applying ecologically-derived concepts with subjective, contextual problems around human resilience. Transferring concepts such as diversity, flexibility, and indeed resilience itself from ecological theory to address human development, which is predicated on ideas around sustainable economic growth, becomes problematic. Similarly, the framing of ecosystems as bundles of services for human use raises ethical issues with respect to prioritising human use above ecological resilience, which require a different, possibly conflicting set of outcomes. One way forward is closer interdisciplinary work between environment and development experts to overcome the challenges highlighted in this review. One option might be to develop a mind-shift away from social-ecological systems, delinking these components of systems and applying different characteristics, measures and objectives to conceptualize and operationalize ES for human resilience outcomes.

In particular, there is a need to understand better the barriers to protecting or restoring ecosystem services in order to preserve their contribution to human resilience. This review lays out the compelling evidence for the contribution of ES to human resilience and the economic case for ecosystem-based approaches. In spite of this, there are many reasons why investment in the protection and restoration of ES might not occur. Thinking back to the resilience processes important for sustainable ES flows, it may be that institutional and regulatory systems are not inclusive, flexible or connected enough. Political economy interests of particular stakeholders and decision-makers may trump the equitable and sustainable management of ecosystems. In developing country contexts, financial resources may be too limited, or resilience needs to great, to accept the longer-term timeframe involved with ecosystem-based approaches. Or simply there may not be enough knowledge or capacity to implement these approaches, even where the benefits are clear. Arguably, the resilience processes outlined in the first part of this paper need to be in place to overcome these significant barriers. For example, polycentric institutions and participatory decision-making processes can allay vested interests. Experimentation and innovation may reduce the lead-in times for ecosystem-based approaches such that these become more viable options for building resilience. Next steps in developing theory and practice in this space should be cognizant of that the role of such processes in leading to resilience outcomes.

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Annex 1: Literature search protocols

Web of Science + BIOSIS

Peer reviewed journal articles only

Limit search to 1999-2014

Research Domains: Science Technology + Social Science + Arts Humanities

Exclusions: Socio-psychological/medical studies, terrorism/security studies

Key journals:

Ecology and Society

Global Environmental Change

Environmental Conservation

Environmental Management

Ecological Applications

Ecosystem Services

Climate and Development

NCC

Ecological Economics

Initial search terms:

Social-ecological resilience

Resilience + livelihoods

Ecosystem-based adaptation

Ecosystem services + health

Ecosystem services + wellbeing

Ecosystem services + livelihoods

Ecosystem services + social capital

Ecosystem services + security

Ecosystem services + hazard

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