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Payments for Ecosystem Services (PES) in the face of external biophysical stressors

Abstract

Economic instruments such as Payments for Ecosystem Services (PES) schemes are increasingly promoted to protect ecosystems (and their associated ecosystem services) that are threatened by processes of local and global change. Biophysical stressors external to a PES site, such as forest fires, pollution, sea level rise, and ocean acidification, may undermine ecosystem stability and sustained ecosystem service provision, yet their threats and impacts are difficult to account for within PES scheme design. We present a typology of external biophysical stressors, characterizing them in terms of stressor origin, spatial domain and temporal scale. We further analyse how external stressors can potentially impinge on key PES parameters, as they (1) threaten ecosystem service provision, additionality and permanence, (2) add challenges to the identification of PES providers and beneficiaries, and (3) add complexity and costs to PES mechanism design. Effective PES implementation under external stressors requires greater emphasis on the evaluation and mitigation of external stressors, and further instruments that can accommodate associated risks and uncertainties. A greater understanding of external stressors will increase our capacity to design multi-scale instruments to conserve important ecosystems in times of environmental change.

Keywords: Blue carbon Ecosystem stability Permanence REDD+ Regime shift Transaction costs

1. Introduction

Many ecosystems are facing severe declines in areal extent and quality due to the impacts of local and global environmental change, with concomitant declines in biodiversity and ecosystem service provision (e.g., Butchard et al., 2010; Dobson et al., 2006; Leemans and Eickhout, 2004). Ecosystem service losses can have profound physical and socioeconomic consequences; for example, tropical deforestation contributes up to 14% of total anthropogenic CO_2 emissions (Harris et al., 2012), while declining fisheries catches represent billions of dollars in annual losses, threatening coastal livelihoods and food security (Ehrlich and Ehrlich, 2013).

The scale of ecosystem service losses due to habitat destruction and degradation have prompted growing interest in Payments for Ecosystem Services (PES) schemes to incentivize widespread conservation measures (Wunder, 2007).

PES schemes involve the transfer of resources between social actors to create incentives that align individual and collective natural resource management decisions with the social interest (Muradian et al., 2010). PES rewards actors that enhance ecosystem service provision, or, most often, compensates them for the costs they bear when stopping practices that act as a stressor. This may involve incentive-based schemes such as direct market transactions, rewards for conservation actions, and/or green subsidies. Although incentive-based environmental protection has been in place for decades, PES gained mainstream attention in the 1990s/2000s following increased awareness of the economic value of ecosystem services (TEEB, 2010). PES schemes have since been implemented in both developing and developed country contexts, targeting a broad range of habitats and ecosystem services (Schomers and Matzdorf, 2013) (e.g., Fig. 1). PES schemes have been targeted for their potential to enhance climate change mitigation efforts at the global scale, by creating new financial incentives to reduce carbon emissions from land use change (e.g., through schemes for Reducing Emissions from Deforestation and Degradation [REDD+] and the conservation of "blue carbon").

However, PES schemes on the ground are often more complex than the simple provision of incentives in exchange for the provision of target ecosystem services (Ghazoul et al., 2010; Muradian et al., 2013). A number of socio-economic and governance factors have been noted to shape PES function, including the governance contexts within which schemes operate (Karsenty and Ongolo, 2011), surrounding land-uses and the leakage of deforestation activities (Wunder, 2008), and a range of social equity dimensions (Pascual et al., 2014) such as underlying land tenure claims, local rights, and benefit distribution (e.g., Beymer-Farris and Bassett, 2012; Larson et al., 2013).

Growing awareness of these types of issues highlights how seemingly 'outside' factors can fundamentally shape PES function. Similarly, there is a need to evaluate the external physical and ecological factors that can also shape sustainable, long-term ecosystem service provision through PES. In particular, biophysical stressors that are external to PES sites, such as forest fires, pollution, temperature changes, sea level rise, and ocean acidifica-tion, can deeply affect ecosystem stability and service provision (Schro¨ ter et al., 2005). Associated uncertainty and risks can add substantial complexity to PES design. We examine the implications of external stressors on effective PES design and operation. We present a typology of external stressors to illustrate their effects on key PES parameters related to (1) defining ecosystem service provision; (2) identifying ecosystem service providers and poten-tial payers; and (3) designing effective PES compensation mechanisms. We further examine mechanisms to cope with external stressors in PES, identifying approaches and strategies to address risk, costs, liability and uncertainty.

2. A typology of external biophysical stressors

2.1. Defining external stressors

External biophysical stressors include a diverse set of (physical, biological and chemical) drivers of ecosystem loss and/or degradation, characterized by origins outside the individual sites targeted for conservation. For instance, external stressors in terrestrial ecosystems may include stochastic weather events and pest outbreaks (Galik and Jackson, 2009), invasive species (Funk et al., 2014) or forest fires (Hurteau et al., 2012). External stressors in aquatic, coastal and marine environments are equally diverse, including increasing nutrient loads from agriculture (Carpenter, 2003), sea level rise (SLR) and ocean acidification (Harley et al., 2006), thermal stress, aquatic invasive species (De'ath et al., 2012), etc; all threats that can affect ecosystem functions and associated services of a targeted conservation area, despite originating outside area boundaries. Ecosystem stressors related to climate change are a particular challenge to habitat managers and land planners, as they are largely outside of their control (Tingley et al., 2014), and are already having clear impacts on ecosystem functioning and service provision (Groves et al., 2012). External stressors in these examples may lead to differing levels of ecosystem service reduction, from low level service disruption to complete ecosystem service loss, depending on stressor scale, magnitude and frequency, and resilience or tolerance of the affected ecosystem/ecological community (McClanahan et al., 2014).

Although diverse in mechanism and process, external stressors can be broadly characterized in terms of origin, spatial scale of impacts, and temporal scales influenced by lag-times (Fig. 2). Some combinations of these three axes are more likely to occur than others, due to scale; for example diffuse stressors are more likely to act on larger scales as they may originate from multiple sources.

2.1.1. Stressor origin

The origin of external stressors ranges from the point source to the diffuse. Point source stressors are comparatively easy to locate for inclusion under PES (e.g., local sewage outflow adjacent to a target site). The diffuse and often invisible nature of some external stressors (such as fluvial nutrient loading from an entire catchment) makes it difficult to readily identify their origin(s) and to establish causal links between stressor sources and ecological impacts (Mcleod et al., 2013). Stressors exacerbated by global climate change, such as coral bleaching, ocean acidification, and sea level rise, are impossible to attribute to a group of defined sources.

2.1.2. Spatial scales of stressor impacts

Depending on the type and mode of external stressor, impacts may be felt over different spatial scales. For example, while direct fire impacts on ecosystem stability and service provision may be relatively localized, diffuse stressors such as atmospheric pollution and are often felt over national, regional and global scales (Holling, 1992; Gunderson and Holling, 2002). The spatial scale over which a given disturbance operates can define the types of ecosystem services that will likely be affected (Hein et al., 2006).

2.1.3. Temporal scales of stressor impact on target ecosystem service

While causal effects from the impacts of some external stressors may be immediately evident (e.g., fire, stochastic weather events), other impacts are long-term and non-linear (e.g., Greˆt-Regamey et al., 2014). For example, low-magnitude, cumulative external stress such as sea level rise can push coastal ecosystems beyond thresholds (Friess et al., 2012) to alternative stable states that may not provide an equivalent level of ecosystem service (Scheffer et al., 2001). Similar risks have been observed with invasive species, which can show time lags before they impact novel habitats (Crooks, 2005). Importantly, such regime shifts are notoriously difficult to predict (Biggs et al., 2009), and challenging to detect over short-medium time scales (Folke et al., 2004). Additionally, the internal connectivity of many systems (especially aquatic systems) means that external stressors often have cascading effects among trophic levels and ecosystems (Carr et al., 2003; Halpern et al., 2008).

2.2. Interactions between multiple external stressors

While external stressors can be characterized individually in terms of origin and scale (Fig. 2), interacting stressors and cumulative impacts over time add further complexity to understanding stressor magnitude and impact, as systems are rarely affected by a single stressor alone (e.g., examples in Section 3). Several authors (Crain et al., 2008; Darling and Coˆte´ , 2008; Brown et al., 2013, 2014; Ban et al., 2014) provide a comprehensive summary of stressor interactions, which can be additive (sum of their impacts in isolation); antagonistic (combined impact is less than the expected additive impact); or synergistic (combined impact is greater than the expected additive impact). Coral reefs in particular are model systems for considering multi-stressor interactions (Darling et al., 2010). For example, (local) coastal pollution can synergistically increase coastal algal growth that can outcompete corals already weakened as a result of ocean acidification (a regional-global stressor) (Bille´ et al., 2013), while fishing and increasing sea surface temperature stressors may show an antagonistic, or weakly additive interaction (Darling et al., 2010). This relationship was not synergistic due to covariance in species response to the stressors, and because one stressor (bleaching) had a stronger influence than the other.

3. External stressors affect ecosystem service provision

The three dimensions to external stressors have important implications for ecosystem service provision, as they shape scales of exposure, impact and intensity (Wilson et al., 2005). Examples from the Brazilian Amazon, the Mississippi Delta (USA) and the Great Barrier Reef (Australia) exemplify the diversity, complexity and magnitude of external stressors, and their influence on ecosystem stability, function and service provision (see Supple-mentary Information for an additional example of stressor impacts on ecosystem service provision in South African shrublands) (Table 1). We provide a range of examples to show the diversity of external stressors and their diverse impacts across different ecosystems. In particular, non-linear changes in ecological thresh-olds can be especially prevalent and unpredictable in the coastal and marine environment (Scheffer et al., 2001), and water-linked systems may be particularly vulnerable to external stressors because of their high internal connectivity due to the aqueous medium (Carr et al., 2003; Halpern et al., 2008; Stoeckl et al., 2011).

3.1. Fire risk in the Brazilian Amazon

The Brazilian Amazon represents one of the largest, most biodiverse tropical rainforests in the world, providing ecosystem services at local (timber, non-timber forest products), regional (pollination, water control) and global scales (carbon storage, climate regulation) (Foley et al., 2007). However, large-scale land use change in the Amazon Basin has severely impacted the provision of ecosystem services such as carbon storage (Torras, 2000; Harris et al., 2012). Thus, emerging PES schemes to incentivize sustainable management and reduce forest sector carbon emissions in the Brazilian Amazon (e.g., REDD+ schemes) could result in widespread forest conservation action, and a 2–5% reduction in global carbon emissions (Nepstad et al., 2009).

Well-enforced REDD+ sites may protect their forest carbon stocks from large losses caused by direct, internal deforestation processes. However, the forest carbon stocks protected in REDD+ sites may still face degradation due to the risk of intentional and unintentional fires that originate from outside the boundaries of a PES scheme, but then subsequently enter the conservation site (Hurteau et al., 2009; Barlow et al., 2012). In the context of the external stressor typology presented previously, such fires are generally point-source, impact ecosystem function relatively quickly and at comparatively local scales (Fig. 2). However, exact stressor dynamics depend on factors such as substrate (e.g., peatland vs. mineral soils), stressor origin (whether originating from land-clearing practices, arson or secondary forest land use management), and fire intensity and movement, which is heavily shaped by forest type and disturbance (see Barlow et al., 2012). Thus, reduced direct deforestation (e.g., through REDD+) does not automatically lead to proportional declines in forest fire risk in the landscape, in fact the opposite relationship may be true due to slash and burn practices in adjacent secondary forest landscapes (Araga˜o and Shimabukuro, 2010).

Fires can additionally reduce the ecosystem resilience of adjacent areas through drying effects, reduced productivity and increased fire risk (Foley et al., 2007). These further interact with other, more diffuse climate-related external stressors (Fig. 2) (e.g., El Nin˜o Southern Oscillation and increased drought periods) to increase fire risk and resultant carbon emissions (Araga˜o and Shimabukuro, 2010; Araga˜o et al., 2014).

Considering the potential risk of fire encroachment into protected REDD+ sites, the impacts of fire on adjacent areas, and their prevalence and potential role in reducing the permanence of forest carbon stocks over large scales, it is surprising that fire risk management has received little attention in the REDD+ policy process and pilot studies (Barlow et al., 2012).

3.2. Wetland loss in coastal Louisiana

The Mississippi Delta in the southern US provides multiple ecosystem services such as enhanced fisheries, habitat refuge, water purification and coastal protection, with an estimated economic value of $12–47 billion per year (Batker et al., 2010). However, 4900 km2 of wetland habitat has been lost since 1900 (Day et al., 2007), with a potential loss and reduction in ecosystem service provision.

Notably, between 1955 and 1978 only 16% of observed habitat loss on the Delta was attributed to direct, local impacts internal to a wetland site, such as draining and spoil deposition (Boesch et al., 1994). Instead, major stressors that reduced or degraded ecosystem service provision have been external to specific wetland sites on the Delta. Stressors vary in their scale and origin (see Fig. 2), principally related to sediment management strategies across catchments, and SLR (Fig. 3). At the national scale, upstream sediment input has been severely curtailed (Blum and Roberts, 2009, Fig. 3a), so insufficient sediment is available to offset a Delta surface elevation that is naturally subsiding due to the compaction of Holocene sediments. This problem is exacerbated at smaller spatial scales by subsidence driven by natural resource extraction adjacent to wetland sites (Morton et al., 2006), and by reduced local sediment input due to flood control dykes adjacent to individual wetland sites that curtail sediment delivery (Boesch et al., 1994; Day et al., 2007).

Thus, the cumulative effects of sediment management and resource extraction, alongside natural deltaic subsidence have made the Delta particularly vulnerable to SLR. The resultant reduction and degradation of ecosystem services has been recognized by the Louisiana Flood Protection Authorities, who recently filed a lawsuit against 97 oil and gas companies for coastal wetland loss that reduced coastal protection services (Schleifstein, 2013).

3.3. Degradation of the Great Barrier Reef

Australia's Great Barrier Reef provides numerous ecosystem services, related to fisheries, tourism, coastal protection, and water purification (Stoekl et al., 2011). The Reef is considered a gold standard of reef management, given its large size (covering 34,870,000 ha within the bounds of the Great Barrier Reef World Heritage Site), long-term conservation status (established in 1981) and relatively low direct human pressure (World Heritage Committee, 2014; Sweatman et al., 2011). Nevertheless, the Reef has experienced major (>50%) decline in coral cover from its initial cover, and has lost 1.45% yr _1 since 2006 (De'ath et al., 2012), with broad documented evidence of the Reef's declining ability to provide ecosystem services (Stoekl et al., 2011).

The three principal stressors responsible for coral loss over the past _30 years are largely associated with external stressors— tropical cyclones, predation by crown-of-thorns starfish and coral bleaching accounted for 48%, 42%, and 10% of respective estimated losses (De'ath et al., 2012). While predatory starfish are themselves not external stressors, their spread was promoted by dramatic increases in external fluvial nutrient and sediment loads (Sweat-man et al., 2011). Development and land use activities adjacent to the Reef have a "fundamental and critical influence on the values [of the Great Barrier Reef]" (World Heritage Committee, 2014). In particular, sediment and nutrient pollution caused by land use change and channel erosion in river catchments that drain onto the reef is a key threat (Brodie, 2014), and phosphorus levels into the Great Barrier Reef from terrestrial sources increased eight-fold between 1949 and 2008 (Mallela et al., 2013). Sediment and nutrient pollution from agricultural sources are diffuse stressors: point source origins are hard to identify, and large lag times exist between initiation of erosion and final downstream deposition in the coastal zone (Wasson and Sidorchuk, 2000, Fig. 2). Reefbuilding corals are experiencing increasing physiological stress due to increasing sea surface temperatures and ocean acidification (Mcleod et al., 2013), which represent particularly diffuse, gradual and global stressors. The potential interaction between the impacts from climate change and catchment/land use change will continue to reduce coral cover and ecosystem service provision in the Great Barrier Reef past the year 2100 (Bohensky et al., 2011), though the interaction between climate change and other stressors such as disease is less clear, with either no clear interaction, or an interaction that is weakly antagonistic (Ban et al., 2013).

External stressors may even affect the Great Barrier Reef's viability as a designated protected area. Recent threats from mining, port development and dredging in and adjacent to the Great Barrier Reef have made international news, especially at Gladstone Harbour and the Abbot Point coal terminal (Petersen, 2014). In view of their impact on the Great Barrier Reef and its concomitant ecosystem services, the World Heritage Committee has requested that the State authorities ensure that development is not permitted where it would impact individually or cumulatively on the Reef, and ensure that developments are not permitted outside pre-existing port areas either inside or adjacent to the Reef (World Heritage Committee, 2013). External biophysical stressors caused by human activities may thus threaten the Great Barrier Reef's designation as a World Heritage Site (World Heritage Committee, 2013).

Efforts have been made to reduce the intensity of some external stressors through PES mechanisms. This is especially the case with soil and nutrient pollution, which has recently been the target of government funding: in 2 years it has been broadly estimated that fluvial sediment loads have been reduced by 6%, at an approximate cost of $72 million (Brodie, 2014). However, the cost of offsetting just one dredge spoil site at Abbot Point could cost as much as $1 billion (Brodie, 2014).

4. Challenges of PES in the face of external stressors

Degradation of the Brazilian Amazon, Mississippi Delta, the Great Barrier Reef (Section 3) and other systems such as African shrublands (see Supplementary Information) illustrate how eco-systems are subject to external stressors of diverse origins that operate at multiple temporal and spatial scales, and can affect ecosystem service provision. Where this occurs, external stressors can potentially present significant challenges to designing and implementing effective PES schemes. Even in the context of comparatively large-scale, well-governed and integrated systems (e.g., Greater Barrier Reef, Mississippi Delta), external stressors can severely impact ecosystem service quality and quantity.

Despite the diversity of PES schemes, these strategies can be broadly characterized by three key operationalizing parameters (sensu Engel et al., 2008). PES schemes generally:

1. Define target ecosystem service(s), establishing a baseline of ecosystem service supply, and the expected conservation outcomes (what services are protected);

2. Identify PES participants, notably service providers (potential receivers of the payment) and beneficiaries (potential payers) (who is engaged by PES to participate in conservation);

3. Design an institutional mechanism whereby ecosystem service beneficiaries compensate ecosystem service providers (how PES schemes are designed and implemented);

Addressing these considerations presents significant challenges in practice (Muradian et al., 2010), challenges that could increase further in the presence of external biophysical stressors. While not all PES schemes are immediately vulnerable to external stressors, and not all external stressors necessarily compromise ecosystem service provision sufficiently over the timescale of a PES scheme, many external stressors have the potential to disrupt the three operationalizing parameters of PES where they (1) affect stability in ecosystem service provision targeted by the scheme (what); (2) complicate the identification of PES participants (who); and (3) increase the transaction costs of PES implementation (how) (Table 2).

4.1. What: service provision, enhancement and permanence

Ecosystem changes that result from external stressors may be gradual, non-linear and cumulative (Scheffer et al., 2001; Greˆt- Regamey et al., 2014; Fig. 2), which poses challenges to identifying, quantifying and monitoring stressor impact on ecosystem services. It can be difficult to attribute degradation to specific stressors — particularly where these are multiple, diffuse, and vary across scales. Additional management challenges arise due to the fact that not all external stressors are equally important (Tingley et al., 2014), and synergistic, additive or antagonistic interactions between stressors complicates the prediction and management of their impacts on ecosystem service provision, because the type of interaction may not be predictable before they happen, or attributable after. Furthermore, the type of interaction between the same stressors may vary spatially (Maina et al., 2011).

In such a context of uncertainty, PES would necessarily face increased monitoring demands and costs, where they seek to protect services impacted by external stressors. For example, protected tropical forest sites may prevent anthropogenic deforestation-linked carbon emissions, but remain vulnerable to external fire events, often determined by land use activities that would have to be monitored throughout the broader landscape

(Barlow et al., 2012). Similarly, wetland loss due to subsidence, and hurricanes in the Mississippi Delta have negatively affected carbon sequestration; deteriorating wetland soils release 147.6 _ 106 metric tonnes of soil carbon per year, valued at _US$27.9 million per year (Delaune and White, 2012). However, subsidence is due to several external stressors and underlying biophysical processes: oil and gas extraction and levee construction blocking sediment input (at the site scale – Boesch et al., 1994; Morton et al., 2006); compaction of Holocene deltaic sediments (at the Delta scale – Boesch et al., 1994); and wider reduction of sediment input due to damming (catchment scale – Blum and Roberts, 2009). It may be difficult to define and monitor the contribution of each stressor. Even if stressors are identified, monitored and attributed to particular impacts, impact time lags and the large scale over which stressors operate mean that mitigation measures for some external stressors (such as increasing sediment input from the wider catchment) cannot be meaningfully applied over payment scheme time horizons.

4.2. Who: identify PES participants

Difficulties in identify stressor origins means that PES schemes may struggle to identify who to pay to reduce these stressors. For example, fluvial pollution impacting the Mississippi Delta has multiple diffuse upstream sources (Mitsch et al., 2001). Identifying and compensating opportunity costs for multiple responsible external actors substantially increases transaction costs (Wunder, 2007), as it requires more resources to identify participants who need to be compensated. Some external stressors may simply be too diffuse and large-scale for their sources to be meaningfully addressed within an individual PES scheme. The Mississippi Delta, for example, is also subject to SLR, associated with greenhouse gasses well beyond the Delta. Addressing such large-scale external stressors resulting from global climate change is beyond the scope of a single-site PES scheme. In contrast, it could be more feasible to identify external participants in the case of relatively local, pointsource stressors, as in the case of fire-based agriculture in the Amazon.

4.3. How: design compensation mechanisms

External stressors can complicate PES optimal design and the mediation of relationships among service providers and bene-ficiaries. For example, ecosystem management taking account of external stressors affecting the Brazilian Amazon and the Louisiana Delta (and other systems, see Supplementary Information) would not only extend monitoring demands and vastly increase the number of local and regional stakeholders involved externally (if they could indeed be identified), but also prolong negotiations over responsibility and compensation amounts, thereby increasing PES operating costs. Trans-state/territory agreements to manage external, or "upstream" land-use decisions (e.g., dams, agriculture) could also increase institutional complexity and the costs of operationalizing PES.

PES compensation design may be complicated where external stressors increase risks to PES participants. A stochastic, external fire event could devastate a forestry carbon project. Such unpredictable stressors may discourage participation, as payment recipients may be held responsible for factors that occur beyond their control. Similarly, service beneficiaries may not secure reliable service provision, and investors may face financial liability (e.g., in carbon markets or biodiversity offsets). These types of risks can disincentivize participation in PES and beneficiaries' willingness to pay, which represents a major challenge to PES design.

5. A breadth of strategies is required to address external stressors

Conscious of external stressors, PES design can identify strategies through which to address the impacts of stressors on service provision (Table 3). We highlight strategies through which to evaluate (Section 5.1), mitigate (Section 5.2) and accommodate external stressors in PES design (Section 5.3), drawing on a range of strategies used in other, non-PES contexts. Importantly, these strategies need to consider the diversity, nature and multiple scales at which stressors impact ecosystem service provision including the unpredictability of their interactions. Understand- ing the different axes that contribute to an external stressor, using the typology presented in Fig. 2, is important to understanding practical implications for the "what, who and how" of PES design (Table 2), and may determine how easily external stressors can be incorporated into PES planning. For example, some stressors can be more readily targeted than others (e.g., those with point source origins); some may impact ecosystem service provision within/beyond PES time frames depending on the temporal scale of their impact, and others stressors may be too geographically distant to be meaningfully integrated into a PES scheme.

5.1. Evaluating exposure and vulnerability to stressors

5.1.1. The need for evaluation

Proactive identification of potential stressors and their expected temporal and spatial scales of impact, origin, and anticipated interactions (Fig. 2, Table 3) is required to ascertain scheme vulnerability. Evaluation of likely exposure, intensity and impacts (Wilson et al., 2005) is critical to informing design and management priorities. Stressor evaluation may identify significant long-term, cumulative impacts, but decide they are of relatively low concern due to PES time horizons, budgets or scope. In contrast, more point-source, local and immediate stressors may be prioritized (Fig. 2). For example, taking into account past records, the risks of fire in Indonesia—particularly around drained peat lands and in proximity to agriculture—should likely inform PES design (Yulianti et al., 2012). In contrast, the external impacts of sea level rise or sediment deprivation on a wetland system in the Mississippi Delta might be deemed beyond the time horizon of a PES scheme.

External stressor evaluation may also clarify whether stressors have been impacting the target ecosystem continuously, or were introduced or increased after PES implementation. This is particularly important where stressors are a function of changing human activities around PES sites (Pressey et al., 2007), and this distinction may have implications for liability and risk management (Section 5.3).

Managers may also need to assess the degree of exposure to multiple interacting stressors at multiple spatial and temporal scales (Maina et al., 2011). This requires robust evidence of stressor impacts, and the type and magnitude of interaction(s) with other stressors. Unfortunately, time lags when an inter- acting impact becomes observable means that we have limited insights into when interacting stressors may have an impact, and the form that the interaction takes. The task of predicting stressor impact is further complicated as the type of stressor interaction can differ spatially, despite the stressor types remaining the same (Maina et al., 2011). Thus, it may be hard to predict stressor interactions based on experiences from other protected sites.

5.1.2. Examples of evaluation strategies

Environmental Impact Assessment: EIA tools could be applied to developments adjacent to PES sites. EIAs are a common tool to assess the impacts of individual anthropogenic modifications on the surrounding environment, but have only rarely been suggested in the context of PES. For example, Wang et al. (2010) conducted an EIA on three hydropower developments in the Jiulong River watershed, Southeast China, and estimated the possible impacts on ecosystem service provision, under the assumption that this watershed could be a candidate for PES. _ Stressor Evaluation Models: EIAs can evaluate the risk of specific, point-source, anthropogenic stressors external to a PES site, though will struggle to evaluate multiple stressors from multiple origins (especially natural stressors) or account for stressor interactions, and associated uncertainty (Section 2.2). Where feasible, Stressor Evaluation Models could help locate schemes in areas that are less vulnerable to the influence of external stressors, particularly if models account for dynamism and interactions among service flows and surrounding biophysical conditions in a spatially explicit way at the landscape-level (McClanahan et al., 2011). Some models do exist for particular external stressors, such as the Sea Level Affecting Marshes Model (SLAMM), that spatially models the impact of SLR on coastal wetlands through time. Despite potential issues related to this modeling approach (e.g., Kirwan and Guntenspergen, 2009), SLAMM has been used extensively by academics and coastal managers. At the national scale, 77% (133/171) of US Wildlife Refuges in the coastal zone assessed for SLR vulnerability using SLAMM (USFWS, 2012). On the site scale, SLAMM has been used to predict the future impact of SLR on tidal marsh ecosystem service provision (Craft et al., 2009).

Stressor Evaluation Models could complement the diverse range of Ecosystem Service Provision Models currently available, that spatially predict ecosystem service delivery at the site (e.g., TESSA – Peh et al., 2013) and landscape scale (e.g., INVEST – Tallis et al., 2013; ARIES – Villa et al., 2014). Some of these models begin to incorporate aspects of stressor impact by modeling ecosystem service provision under different habitat states and scenarios, and some model have the ability to estimate uncertainty using a Bayesian Network approach in a form that is accessible to managers (e.g., Villa et al., 2014). Even in the absence of robust datasets and models, a strong understanding of the context in which a scheme operates and a mapping of anticipated stressor pathways can help planners to evaluate the nature and likelihood of stressor impacts (e.g., Wilson et al., 2005; Mattson and Angermeier, 2007). However, linking models of externals stressors and ecosystem service provision may involve tradeoffs; locations most vulnerable to external stressors may face reduced ecosystem service provision, but may offer greatest additionality, and may also represent sites with the greatest human need for PES investment.

Large-scale threat evaluation: Models that seek to understand the processes behind external stressors, and their impacts on ecosystem service provision, can lead to evaluation of stressor threat and system vulnerability. For example, remote sensing can be used to identify forested areas at high risk of fire during planning for forest carbon schemes (Barlow et al., 2012). Similar evaluations may be particularly important to consid-ering cumulative stressors (Halpern et al., 2008), though will require evaluations at multiple scales. This is important because identifying influential local-scale stressors that can be mitigated or accommodated may reduce the severity of larger-scale, diffuse stressors that cannot be easily managed through PES (e.g., managing local nutrient pollution to reduce the impacts of ocean acidification on corals, Bille´ et al., 2013). An understanding of potential small and large scale antago- nistic and synergistic stressor interactions can be used to map areas of greatest threat, and areas where local management interventions may have the greatest impact (see Brown et al. (2014) for example mapping terrestrial pollution and sea surface temperature interactions on seagrass ecosystems in Southeast Asia and Australasia), or where habitat restoration efforts may make the greatest contribution (Allan et al., 2013).

5.2. Mitigating external stressors through higher-order management

5.2.1. The need for mitigation planning through higher-order management

Stressor evaluations can be used to target mitigation efforts on the most influential external stressors, in the most appropriate areas (Ban et al., 2014). However, mitigating external stressors is difficult in some instances due to a mismatch in scales between where a stressor originates, and where its impact is felt (Satake et al., 2008). Where site-specific PES schemes have little leverage to address external stressors, a broader integrated management approach represents a prospective strategy for mitigating some diffuse, larger-scale external stressors (Table 3). In addition to the incorporation of large-scale stressor evaluations, broader integrated management approaches may also be able to incorporate multiple levels of governance and complex linkages that comprise socio-ecological systems (Ostrom and Cox 2010). A framework that contextualizes PES schemes within the broader biophysical, socio-economic and institutional landscape would not only recognize interactions with external stressors, but would facilitate efforts to identify and engage PES participants (providers and beneficiaries) through stakeholder analysis and deliberative platforms, including up- and across-stream communities at large spatial scales, that may be causing external stressors. Notably, PES schemes capable of considering larger spatial and temporal scales may rely on the involvement of higher-order governance units (e.g., provinces, states, intergovernmental organisations, sensu Agrawal, 2003) for successful implementation.

5.2.2. Examples of higher-order mitigation and management strategies

- Moving from site-scale to landscape-scale PES: Despite challenges (sensu Fisher et al., 2010), there are notable examples of effective landscape-level PES. For example, the 518,000 ha water catchment serving New York City, USA has been protected through PES since 1997 to improve drinking water quality. Upstate landowners have been paid by the City to preserve and enhance the watershed and reduce agricultural runoff, at an original estimated cost of US$1.4–1.5 billion over 10 years (Postel and Thompson, 2005; Grolleau and McCann, 2012). Similarly, REDD+ forest carbon policies in many tropical developing countries are also increasingly discussed at the landscape-level, requiring coordination across broad geograph-ic areas and governance units, and linked to land use planning at multiple levels (e.g., Nepstad et al., 2011; Barlow et al., 2012; Knoke et al., 2012).
- Cross-sectoral Planning Framework: A cross-sectoral planning approach is needed to manage external stressors and resolve conflicts between different activities. This may include EIAs for activities external to, but within the vicinity of PES schemes (as above), but this may help plan mitigation measures for selected stressors only. Successfully capturing a wider range of partici-pants and activities requires a

framework for landscape-scale, cross-sectoral planning. Amazonian forest conservation depends on practices and policies in other sectors, including agriculture (Nesptad et al., 2009), and the conservation of the Mississippi Delta relies on measures taken by the oil and gas industry, and policies relating to national catchment water management. Frameworks already exist that can facilitate transparent and stakeholder-inclusive cross-sectoral zoning, such as Systematic Conservation Planning. This framework has also been adapted to include the eternal impacts of climate change (Groves et al., 2012).

- Identifying the key stressors for mitigation: While a higher-order approach to encompass multiple stressors and participants can be important for PES, it may not be feasible in some settings. In these instances, mitigation should focus on stressors with the greatest single impact, the stressor with the most important interaction with other stressors (Tingley et al., 2014), or where local management is most likely to increase ecosystem resilience (Ban et al., 2014). For example, catchment management to reduce nutrient loadings into the Great Barrier Reef could increase the resilience of reefs to coral bleaching, and is a smaller-scale management intervention that is easier to imple-ment compared to interventions that reduce global climate change (Wooldridge, 2009). However, poor understanding of the type of interaction (e.g., synergistic, additive or antagonistic) between strategies may render a single-stressor mitigation approach ineffective in some cases. 5.3. Accommodating external stressors through financial instruments 5.3.1. The need for accommodation Even in the context of integrated, higher-order management, mitigating time-lagged and diffuse external stressors may not be possible, practical or cost effective (sensu Wasson and Sidorchuk, 2000; Halpern et al., 2008). Beyond evaluation and mitigation efforts, schemes must also accommodate remaining uncertainty and risks (Table 3), in order to ensure PES participation remains attractive. Historically, risk has largely been ignored in PES investments (e.g., forest carbon investments, Hurteau et al., 2009) or managed in an ad-hoc manner (Martin, 2013), and service providers have often lacked information on financial risks of PES (Phelps et al., 2011). Yet, coordinated Financial Risk Management (FRM) strategies could potentially manage parti- cipants' exposure to risk as a result of external stressors. Instruments within an FRM framework can help to both identify and measure potential risks, and create strategies for accommo- dating risk. Strategies in this direction can be seen as investments in 'insurance value' to promote resilience and buffer risks (TEEB, 2010).

5.3.2. Examples of accommodation strategies

- Third party ecosystem service insurance could offset costs of underperformance or project failure (Mills, 2009; Bell and Lovelock, 2013), including due to external stressors. Despite limited application to PES schemes, public and private agricultural insurance is regularly used to provide insurance in cases of reduced crop yield due to climatic events such as hail, rain and drought. However, this can be an expensive mechanism to manage and implement, with up to 60% of premium costs to insure US crops subsidized by the Federal Government (Coble and Barnett, 2012). Additionally, insurance instruments may not be viable where risks are very high (Phelps et al., 2011) or where stressors are gradual (Bell and Lovelock, 2013).
- Special purpose underwriting vehicles have aided investment in other high-risk environmental schemes such as renewable energy projects (UNEP, 2004), and may

be appropriate for PES investments involving small PES schemes that may not be able to adopt other accommodating measures, or where public sector support is needed to bridge the gap between developers, investors and financial insurers.

- Credit buffers are one of the few risk management strategies currently applied to PES schemes, and involve precautionary savings to reduce participants' exposure to financial risks (Hurteau et al., 2009). Credit buffers require that a portion of PES funds be set aside to offset losses due to disturbance or stochastic external stressors such as fires (Hurteau et al., 2009, 2012; Phelps et al., 2011). Credit buffers for individual sites have been incorporated into several individual REDD+ projects in the Brazilian Amazon, including the Juma REDD+ project in Amazonas State (10% of Verified Emissions Reduction (VER) credits held back as a buffer), the Genesis REDD+ project in Tocatins State (20% of VER credits) and the Ecomapuaˆ REDD+ project in northern Para´ State (20–40% of VER credits) (Cenamo et al., 2009). Credit buffers pooled from multiple sites have also been suggested for REDD+ projects in Latin America, in order to spread risk, including those of external stressors, across multiple sites (FONAFIFO, CONAFOR & Ministry of Environment, 2012).

6. Conclusions

As PES expands in scope, financing, and into novel ecosystems (e.g., coastal and marine), schemes are likely to face uncertainty and complexity associated with external stressors, and their various interactions (whether synergistic, additive or antagonistic) introduces uncertainty and complexity that we may still be struggling to adequately incorporate into PES scheme design (sensu Barlow et al., 2012). Critically, the broadened approach required in order to integrate external stressors into PES planning introduces additional governance challenges and costs (Dietz et al., 2003), in addition to the range of socio-economic and governance challenges that PES schemes already face. Notably, efforts to address external stressors may rely on linking individual PES schemes to higher-order governance institutions (see Agrawal, 2003; Ostrom and Cox, 2010). Incentives for free riding; institutional complexity associ-ated with large-scale resource management; mismatches between institutional and ecological systems, and difficulties of governing interconnected and evolving social-ecological systems, are exac-erbated in the context of external stressors. Even in the context of relatively strong environmental governance (e.g., the Mississippi Delta, the Great Barrier Reef), external stressors remain a leading threat and major management challenge. The management challenges are even greater in low governance contexts (e.g., Karsenty and Ongolo, 2011) and where data gaps make it even more difficult to identify relationships between external stressors and ecosystem services.

Some of the evaluation, mitigation and accommodation measures described here have been implemented in PES design or for other environmental assets, such as credit buffers and agricultural insurance. However, they have been implemented in isolation, and in some cases, fully mitigating and accommodating external stressors with such instruments may simply not be possible, practical or cost–effective. Mitigating small-spatial scale external stressors may do little to counter the synergistic impacts of severe global climate change (Brown et al., 2013).

Importantly, many proposed accommodation instruments to manage risk assume that ecosystem services are transferable (e.g., atmospheric carbon emissions), though services such as biodiversity, fisheries and water catchment protection are not equally fungible (Salzman and Ruhl, 2000; Phelps et al., 2011). Even in instances where mitigating and accommodating external stressors is theoretically possible, the additional efforts required may increase PES mechanism complexity and transaction costs beyond what is economically viable. For example, increased research and monitoring to detect impacts of external stressors can be expensive and time consuming, or even unfeasible where data is absent. Similarly, broadening project scope to higher order management at the landscape level to account for external stressors will also increase mechanism complexity and transaction costs, as a result of expanded negotiations and payments to external stakeholders, and use of FRM tools to reduce participant risk. Addressing such complexity through individual negotiations could result in unbearable transaction costs. In these cases, public bodies may be necessary to cluster multiple actors in large-scale PES schemes (Vatn, 2010), as has happened in national payments schemes in Costa Rica and Ecuador. This may explain why in practice the vast majority of PES funding comes from public bodies (Milder et al., 2010) rather than from direct beneficiaries.

Sustainable PES efforts cannot afford to overlook the external processes that often shape ecosystem service provision. We must be prepared to evaluate, mitigate and accommodate external stressors within the context of PES design. In some contexts, increased awareness about external stressors may mean that additional costs and complexity are successfully internalised into PES scheme design. Elsewhere, additional costs associated with external stressors may be offset by governments or NGOs, in the same way that some socio-economic externalities are currently absorbed. This has largely been the case with the contextual social and governance factors shaping REDD+ development in particular, where donors, national governments and NGOs are providing support to address factors such as environmental governance and tenure clarity to help facilitate successful PES project development. However, elsewhere, high complexity and transaction costs may mean that a traditional PES approach may not be suitable in some settings that are heavily threatened by external stressors. The practical, management and policy implications of external stressors must be fully considered and integrated into scheme design if we are to improve the utility of PES to conserve imperiled ecosystems in the context of rapid global environmental change.

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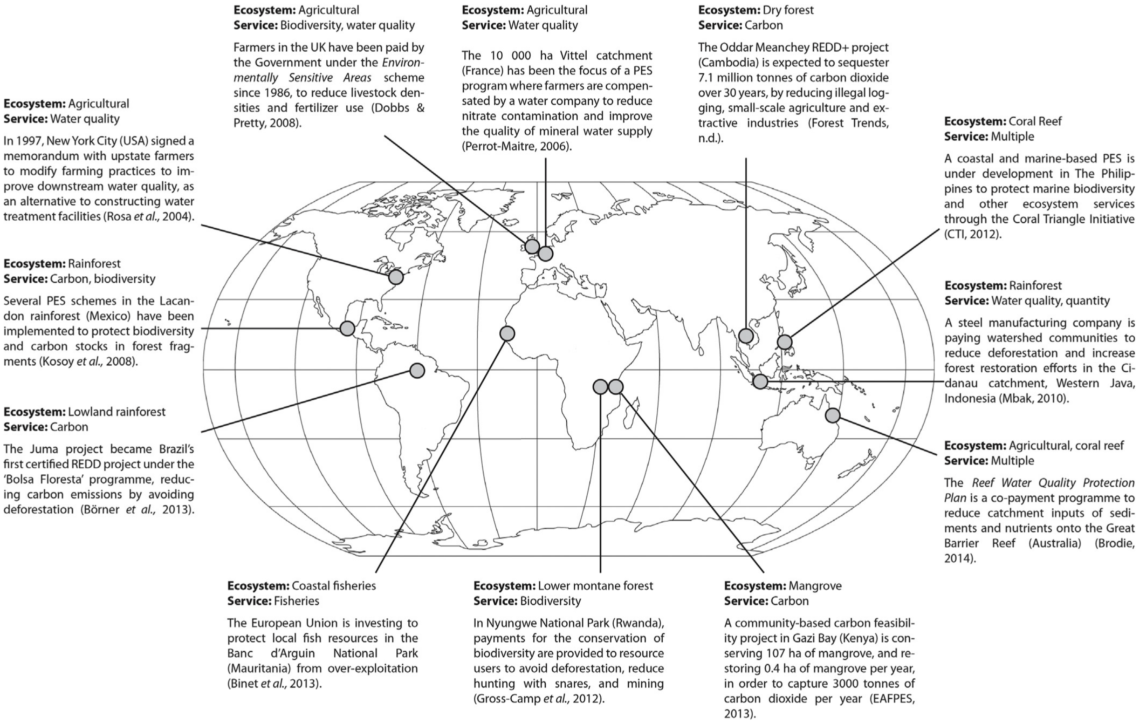


Fig. 1. Payments for Ecosystem Services schemes have been established, or are proposed across a range of ecosystems and regions, targeting different services, and relying on diverse governance arrangements. See References (Binnet et al. (2013), Borner et al. (2013), CTI (2012), Dobbs and Pretty (2008), EAFPES (2013), Forest Trends (n.d.), Gross- Camp et al. (2012), Kosoy et al. (2008), Mbak (2010), Perrot-Maıˆtre (2006), Rosa et al. (2004) and Woolridge (2009)).

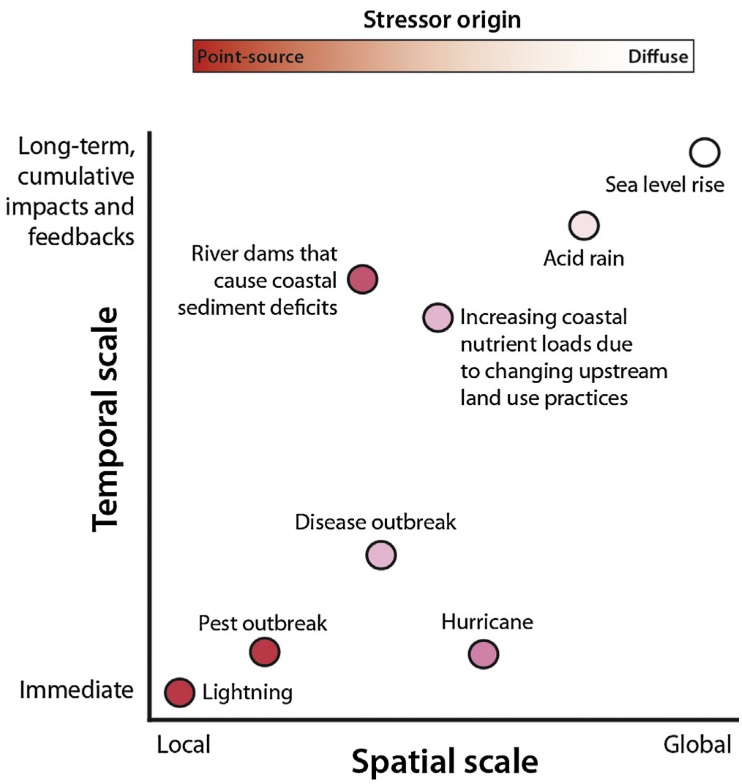
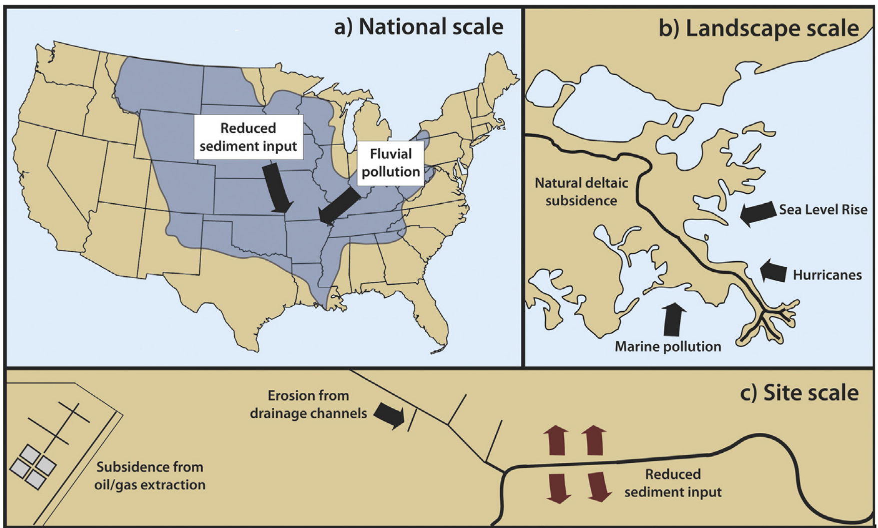


Fig. 2. Illustrative examples of external stressors characterized in terms of (1) the nature of their origin, (2) the spatial scale of impact, and (3) the temporal scale of impact. Note: some external stressors may also interact synergistically or antagonistically (see main text), and may act over multiple scales depending on setting.



Documented external stressors and their impacts	Stressor origin	Spatial scale	Temporal scale
Upstream dams and diversions reduce sediment inputs by~50% (Blum and Roberts 2009)			
Upstream industry and agriculture release pollutants: nitrogen (Mitsch et al. 2001), heavy metals, organophosphates			
***Deepwater Horizon* oil spill** results in marine pollution affecting Delta ecosystems at multiple trophic levels			
Hurricanes Katrina and Rita result in ~100km^2 of wetland loss (Day et al. 2007)			
Holocene fluvial sediment compaction results in deltaic subsidence (Boesch et al. 1994)			
Sea level rise, coupled with **subsidence** and **reduced sediment input**, results in land loss of 13,500 km^2			
Oil and gas extraction results in subsidence and wetland loss (Morton et al. 2006)			
Flood control dykes disconnect sediment input to the deltaic plain (Boesch et al. 1994)			
Local drainage canals result in wetland erosion (Boesch et al. 1994)			

Point-source / local / immediate stressors **Diffuse / large-scale / long-term stressors**

Fig. 3. External stressors affecting the Mississippi Delta, conceptualized in terms of spatial scale, temporal scale and stressor origins (see Fig. 2).