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Environmental compensation for biodiversity and ecosystem services: A flexible framework that addresses human wellbeing

Scott Cole [a,*], Per-Olav Moksnes [b], Tore Söderqvist [c], Sofia A. Wikström [f], Göran Sundblad [d], Linus Hasselström [e], Ulf Bergström [g], Patrik Kraufvelin [g], Lena Bergström [g,*]

[a] *EnviroEconomics Sweden Consultancy, Grantäppevägen 3, 461 58 Trollhättan, Sweden*
[b] *Department of Marine Sciences, University of Gothenburg, Box 461, 10 40530 Gothenburg, Sweden*
[c] *Anthesis Enveco, Barnhusgatan 4, 111 23 Stockholm, Sweden*
[d] *Swedish University of Agricultural Sciences (SLU), Department of Aquatic Resources, Institute of 16 Freshwater Research, Stångholmsvägen 2, 178 93 Drottningholm, Sweden*
[e] *KTH Royal Institute of Technology, Department of Sustainable Development, Environmental Science 20 and Engineering, Teknikringen 10B, 100 44 Stockholm, Sweden*
[f] *Stockholm University, Baltic Sea Centre, 106 91 Stockholm, Sweden*
[g] *Swedish University of Agricultural Sciences (SLU), Department of Aquatic Resources, Skolgatan 6, 25 742 42 Öregrund, Sweden*

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ABSTRACT

Environmental compensation should address negative impacts from human activities on nature, including loss of biodiversity and ecosystem services. However, successful compensation, achieving no net loss, requires broad quantitative information on different types of losses and gains. We find that the scope of compensatory schemes varies in what is considered compensable, which makes it challenging to apply a conceptual approach consistently across schemes with different needs. We propose a flexible yet structured framework for determining which values should be compensated and how. Our framework focuses specifically on habitat deterioration and is illustrated with a case study involving loss of eelgrass habitat. The framework helps identify compensation needs and selects among suitable compensation options, merging science-based information with normative issues and local concerns. By integrating the ecosystem services cascade model, it encompasses aspects from biodiversity structure to human wellbeing. The framework prefers *in-kind* compensation because this targets the structure level and thus meets compensation needs in all subsequent levels of the cascade model; further, it is more likely to capture non-instrumental values (i.e. in nature) and reduce exposure to uncertainty. We highlight the importance of spatial aspects of ecosystem functions, services and their subsequent impacts on wellbeing. Although our selection hierarchy assumes a “similar and nearby” principle for habitat restoration (preference for *in-kind/on-site*), this criterion is not universal. We underscore the hierarchy’s implicit normative assumptions and suggest that apparent disagreement about *who* should benefit may be traced to an unresolved conflict between egalitarianism and utilitarianism.

1. Introduction

Human wellbeing[1] is dependent on environmental assets and flows provided by nature. Together, these contribute to the provision of ecosystem services, sometimes collectively referred to as natural capital (Haines-Young and Potschin, 2018; Hernández-Blanco and Costanza, 2018; Missemer, 2018). Examples of these services include water purification, climate regulation, provisioning of food and raw material, and enabling recreational activities (de Groot et al., 2012; Maes et al., 2016). A diverse suite of human activities causes environmental pressure on ecosystems. This has caused, in turn, a global loss of biodiversity and deterioration in the supply of ecosystem services in both terrestrial and aquatic environments (Brondizio et al., 2019). Even relatively small deteriorations of ‘everyday landscapes’ may add up to significant

* Corresponding authors.
E-mail addresses: scott@eesweden.com (S. Cole), per.moksnes@marine.gu.se (P.-O. Moksnes), tore.soderqvist@anthesisgroup.com (T. Söderqvist), sofia.wikstrom@su.se (S.A. Wikström), goran.sundblad@slu.se (G. Sundblad), plh@kth.se (L. Hasselström), ulf.bergstrom@slu.se (U. Bergström), patrik.kraufvelin@slu.se (P. Kraufvelin), lena.bergstrom@slu.se (L. Bergström).

[1] We use human wellbeing and human welfare as synonyms.

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cumulative losses across various geographic scales (Steffen et al., 2015; Whitehead et al., 2017).

In response to large-scale environmental deterioration, various policies are put in place to support protection and long-term sustainability. Countries have committed nationally and via global agreements to environmental goals for biodiversity and the supply of ecosystem services, including an effort to halt current rates of deterioration or improving the situation (see e.g., EC, 2011, 2020; CBD, 2011a; UNDP, 2016; Maron et al., 2018; IPBES, 2019). Further, government policies that make visible nature's contribution to welfare, such as the information and signaling effects from environmental taxes, has likely contributed to engagement of the private sector through e.g., natural capital assessment accounting (Peiffer and Haustermann 2017). Broker functions such as habitat banks are for example set to help match suppliers of ecosystem services with developers that need to invest in them (Froger et al., 2015; Boisvert, 2015; Hahn et al., 2015; OECD, 2018).

However, sustainability goals require additional concrete actions. In this setting, environmental compensation is put forward as one potentially promising tool (CBD, 2011a; EC, 2011, 2019; Coralie et al., 2015). Sometimes referred to as biodiversity offsets[2], and often used in conjunction with habitat banking or other mechanisms (Koh et al., 2017), environmental compensation may suggest a way to allow essential development such as energy, housing, transportation, infrastructure, while reducing or neutralizing any associated deterioration of environmental assets and flows. Environmental compensation focuses on the resource itself, i.e. compensation is "paid" to the public in terms of environmental resources rather than money (e.g. Cole 2011). In practice, compensation can take the form of projects that restore and/or improve common resources through measures such as habitat restoration, species rehabilitation and/or resource enhancement designed to offset the impacts of environmental damage. Compensation has also been used *ex post* to address actual impacts following e.g., oil spills (Payne, 2016; Lipton et al., 2018; US DOI, 2019).

As a policy intervention, environmental compensation requirements can address two recognized market failures[3] known to acerbate environmental deterioration: (1) the lack of ownership, which precludes return on investment and, thus, a key incentive for managing assets sustainably; and (2) the lack of price signals, which can preclude a full accounting of the net social benefits associated with environmental assets and flows. This is critical, since the failure to recognize such benefits is known to lead to poor decision-making both publicly and privately as markets still tend to be decisive for when and how environmental assets and flows are consumed (Daily et al., 2009; Guerry et al., 2015; Hahn et al., 2015; Costanza et al., 2017). Environmental compensation requirements essentially shift the burden of environmental damage costs from the public to the "polluters", who must now consider compensation costs in their decision-making.

However, the compensation mechanism means that some individuals will necessarily be better off and others worse off following a compensation, assuming for example effects of localization decisions, time lags, or differences in preference among individuals. In fact, a Swedish *ex post* analysis of offsetting found an un-balanced distribution of costs and benefits associated with compensation, which raises normative questions of equity in compensation selection (Mellin et al. (in prep); see also Levrel et al., 2017 regarding re-distribution of benefits). A participatory process that investigates the preferences of those affected by the damage and/or compensation ("affected individuals") may improve equity outcomes (assuming vocal minorities do not exert disproportionate influence). However, the process itself should also be framed within authorities' responsibilities regarding legal obligations and environmental objectives, including consideration of future generations (IPBES 2019).

Implementation of environmental compensation has also been criticized because it can be difficult in practice to balance *successfully* losses with gains (Josefsson et al., 2021). Opponents suggest that application of environmental compensation may in fact aggravate environmental deterioration by encouraging development in exchange for only symbolic restoration projects or an overemphasis on "easy-to-implement" compensation projects that fail to account for complex ecosystem impacts (McKenney and Kiesecker, 2010; Howarth, 2013; Coralie et al., 2015; Maron et al., 2016). Other critics underscore the importance of measuring human preferences to accurately account for impacts on wellbeing, which may be overlooked when simply matching biophysical loss with a biophysical gain (e.g., offsite bird restoration and viewing platform that is inaccessible to birdwatchers; Cole, 2011; Lipton et al., 2018).

Further, as an economic concept, compensation is inextricably linked to the "value" of a (lost) good, service or other benefit; in particular, which values should be compensated, how, and for whom? A fundamental demarcation in defining value can be found in two different philosophical viewpoints toward nature (e.g. Griffiths et al., 2019; Karlsson and Edvardsson Björnberg, 2020). On the one hand, an anthropocentric viewpoint focuses on the instrumental role of nature in enhancing human wellbeing. In contrast, a non-anthropocentric viewpoint, such as zoocentrism, biocentrism and ecocentrism, emphasizes nature's own moral standing, where the value of animals and other forms of life can be motivated by its own existence, independent of any benefit it may provide humans (CBD, 2011a; Vucetich et al., 2015). In relation to environmental management, we consider both of these philosophical viewpoints to apply, in the sense that nature can have instrumental value (for humans) as well as non-instrumental value. Further, their distinction can be helpful in assessing compensation needs.[4]

The purpose of the paper is to present a conceptual framework for describing environmental damage in connection to physical development and other human impacts on land use, identifying subsequent compensation needs, selecting preferred compensation options, and evaluating outcomes. The framework centers around habitat loss or deterioration and the resulting loss of ecosystem function and ecosystem services. It can be used to support national and local processes by suggesting how actions to halt losses to biodiversity and ecosystem services can be identified and planned to address effects of human activities. Given this overarching aim, the framework is applicable in a variety of environmental settings (terrestrial or aquatic), policy scenarios (e.g., expected damage *ex ante* or actual damage *ex post*), and regulatory contexts aligned with the global sustainable development goals (see also below and Table 1).

The framework's contribution is providing a transparent set of options for decision-makers on how to select the most appropriate and precise compensation. It is, hence, not prescriptive, but helps decision-makers navigate the trade-offs and complications that arise in scaling compensation We present an example based on losses of habitat-forming marine eelgrass and consider a suite of hypothetical compensation options to underscore the real-world challenges faced by managers, including the need to evaluate *off-site* and *out-of-kind* options. Importantly, we examine environmental compensation as a tool to address

[2] *Environmental compensation* describes a concept that can be represented by similar terms, which can contribute to confusion around its intent and extent. The literature also refers to *biodiversity offsetting, compensatory mitigation, compensatory measures*, etc.

[3] Often defined as when a competitive market fails to produce an "optimal" outcome for society. Welfare economists study factors that can lead to market failure, the potential size of the subsequent welfare loss, and how/if governmental intervention can steer these scenarios toward outcomes that increase social wellbeing (Johansson 1993).

[4] Note that non-instrumental value is frequently referred to as intrinsic value, although final value has been suggested as a more appropriate term, see Peterson and Sandin (2013).

Table 1
Overview of some legal, regulatory and policy schemes and their apparent emphasis on nature's instrumental vs. non-instrumental values.

Scheme	Relevant text	Lawmakers' apparent emphasis on relevant values to consider
Convention on Biological Diversity (CBD 2011b)	The CBD Strategy for Resource Mobilization includes an indicator about "...*new and innovative financial mechanisms, which consider intrinsic values and all other values of biodiversity*" (p. 6), where biodiversity offset mechanisms are mentioned as one example of such mechanisms (p. 20).	Instrumental+Non-instrumental
Bern Convention on the Conservation of European Wildlife and Natural Habitats (Bern Convention 1979)	The 1979 Bern convention recognizes that "[…] *wild flora and fauna constitute a natural heritage of aesthetic, scientific, cultural, recreational, economic and intrinsic value that needs to be preserved and handed on to future generations*" (Preamble)	Instrumental+Non-instrumental
The European Union Habitats Directive (EC 2007)	A development project may only be permitted (and thus require compensation projects) if there is an "*overriding public interest*", suggesting anthropocentric values may trump negative impacts on environmental values (p. 3. Sec 1.1) If a project goes forward, "*The opinion has to cover the assessment of the ecological values . likely to be affected*" (p. 23. Sec 1.8.3) Compensation projects should "*[restore] the habitat to ensure the maintenance of its conservation value*" (p. 14. Sec 1.4.3)	Unclear
United States NRDA (US OPA, 1990; US DOI, 2019)	Purpose is to "*make the environment and public whole for injuries to natural resources and services,*" a clear reference to a welfare economics concept. Compensation projects are expected to offset economic damages (US OPA 1990, Sec. 990.10).	Instrumental value
The European Union Biodiversity Strategy (EC, 2011, 2019, 2020)	The previous 2020 goal: "*The EU 2020 biodiversity target is underpinned by the recognition that, in addition to its intrinsic value, biodiversity and the services it provides have significant economic value that is seldom captured in markets.*" (p. 2, EC, 2011) The revised 2030 strategy (EC, 2020) builds on methods consistent with " … *forward-looking, sustainable policy and planning processes [that] seek to improve ecosystem condition … [and that] improve biologically diverse, multifunctional ecosystems for their intrinsic value, as well as for their benefits to people and the economy*." (EC, 2019, p. 18.)	Instrumental+Non-instrumental
Business and Biodiversity Offset Program (BBOP, 2012)[1]	States that "*Although the PCI* [Principles, Criteria and Indicators] *focus on the ecological aspects (i.e. intrinsic values) of biodiversity, the principles also embrace its socioeconomic and cultural values*" (p. 1).	Instrumental+Non-instrumental
Swedish Environmental Code and Swedish EPA Guidelines on Environmental Compensation	Swedish Code notes that "…*Nature is recognized to have an independent protective value*" *and "Besides nature's protective value in itself, nature and its resources are a precondition for economic productivity, welfare and human survival.*"[3]Swedish EPA guidelines on compensation notes that "…*nature's value … includes the provision of ecosystem services, but also includes its own inherent protective value, including that of biological diversity itself.*"[2]	Instrumental+Non-instrumental

[1] Although BBOP has now completed its work and no longer exists, it has been an industry standard (see ten Kate et al. (2018))
[2] Translated from Swedish (Swedish EPA (2016), p. 25).
[3] Translated from Swedish. Swedish Environmental Code description is based on a Statute comment in Swedish Government Bill 1997/98:45, p. 9. See also Strömberg (2016).

residual losses of biodiversity and ecosystem services, assuming necessary mitigation has already been undertaken to avoid and minimize damages for permitted projects that are otherwise deemed appropriate (BBOP, 2012; Arlidge v, 2018).

We believe that a "structured flexibility", as enabled by the framework, is needed to help decision-makers conceptualize and implement compensation in way that it is useful across a variety of relevant regulatory contexts (see also Table 1): *legal requirements* (e.g., to enforce polluter pays principle, to ensure accountability to the public); *policy obligations* (e.g., to meet regional/global environmental objectives, to follow best practices); and *normative judgements* that can arise when considering "affected individuals". We acknowledge that providing options for the compensation process is key to its successful implementation – especially when compared to the alternative of no or insufficient offsetting of residual damage – but a very high degree of flexibility admittedly increases risks for loss of biodiversity and ecosystem services (Bull et al., 2015). The proposed framework suggests how to reduce risks by making visible and safeguarding the full range of values to be compensated, while also addressing equity concerns via public participation.

The framework prevents excessive flexibility through its theoretical anchoring in the concept of ecosystem services as a systematic means for communicating how humans interact with, and are dependent on, ecosystems (Alcamo and Bennett 2003), integrating the ecosystem services cascade model to define the final outputs from an ecological system that benefit people (Haines-Young et al., 2012; Boyd et al., 2016; Haines-Young and Potschin, 2018). In a damage assessment context, our focus builds upon previous work in assessing impacts on nature values and their pathways (Elliott et al., 2017; Bryhn et al., 2020). Globally, the use of environmental compensation is shifting from a primary emphasis on offsetting biophysical changes to a wider scope that considers the benefits ecosystems provide people (EC, 2011, 2019; Tallis et al., 2015; Bouwma et al., 2018; Griffiths et al., 2019; Lipton et al., 2018; Maron et al., 2018). As Sonter et al. (2020) note, this new scope increases the complexity of offsetting since it requires additional trade-offs between relevant benefits.

The rest of the paper is organized as follows: Section 2 describes the underlying concepts to support our framework, which is then presented in Section 3. Section 4 illustrates the framework through a case study and Section 5 discusses implications of integrating the cascade model and our resource-based principles into a compensatory assessment.

2. Underlying concepts

2.1. Compensable values

Table 1 provides a list of some of the legal, regulatory and policy schemes of relevance for environmental compensation and how these vary in their approaches to nature's instrumental and non-instrumental values (see also Ives and Bekessy 2015). The purpose of this non-exhaustive list is to highlight a few examples of relevant policy contexts, which emphasize the importance of addressing different types of compensable values in a framework. For example, the US framework for Natural Resource Damage Assessment that focuses on making the "public whole" following environmental damage (US OPA, 1990; US DOI, 2019) is clearly anthropocentric, with explicit and exclusive reference to instrumental values. Other schemes embrace a broader perspective in which non-instrumental values may be considered compensable (e.g. BBOP 2012). Although Table 1 provides only an indication of the variability across schemes, motivations based exclusively on non-instrumental values appear rare, although such values are used as one type of motivation for introducing legal rights for nature (Chapron et al., 2019). However, as noted by Ives and Bekessy (2015), it is generally difficult to discern the fundamental intentions as the language tends to be somewhat ambiguous. Further, terms describing values are often used differently across disciplines. However, practitioners and the scientific literature are increasingly suggesting that both types of values should be considered in compensatory assessments, reflecting commitments taken by countries under the international Convention on Biological Diversity (CBD, 2011a; Griffiths et al., 2019).

2.2. Cascade model and compensation

By addressing how changes in ecosystem structure and function affect the supply of ecosystem services and associated human benefits, our conceptual framework adheres to the cascade model developed by e.g. Haines-Young et al. (2012) and La Notte et al. (2017). In our adaptation of this model (Fig. 1), ecosystem structure is represented by habitats and habitat-forming species, which on the one hand has non-instrumental values and on the other hand, forms the enabling basis for all functions occurring in the ecosystem, the provision of ecosystem services and subsequent human benefits. Hence, any residual impact of human activity on ecosystem *structure* may, via 'cascading effects', result in further impacts on ecosystem *function*, *services* and/or *benefits*. Note that impact on the *structure* level are primarily attributed to physical pressures, such as habitat loss or habitat replacement, but that impacts can also first occur on any of the other levels, with subsequent 'cascading effects' depending on the type of originating human-caused pressure. The cascade model is integral to our framework, not only because it enables understanding and measuring of both losses (negative impacts from the environmental damage, Fig. 1) and gains (positive impacts from compensation designed to offset losses, see Section 3), but also because it plays a key role in communicating a compensation assessment with stakeholders.

In our framework the *structure* and *function* levels can be interpreted as representing both instrumental and non-instrumental values, as in Fig. 1. In this way the framework adheres both to those ecosystem service classifications in which biodiversity is considered an ecosystem service *per se,* contributing instrumental value, and those where it is considered separately, i.e., also contributes value independent of human wellbeing (as discussed below, this suggests advantages of aiming compensation at the *structure* level).

2.3. Context and definitions

Our framework is place-based in the sense that it is applied with respect to impacts occurring in a specific location. It is intended to support decision-making primarily at the last step in the mitigation hierarchy for project implementation, which aims to first *avoid*, then *minimize*, subsequently *restore*, and finally *compensate* any remaining negative environmental impacts (BBOP, 2012; Arlidge et al., 2018). Thus we define environmental compensation as a tool to offset any residual loss associated with the interfering human activity (Enetjärn et al., 2015), *after* appropriate mitigation measures are undertaken at the damage site.

In our approach, a resource-based compensation project may consist of one or several individual measures, which can be aimed at compensating either the impacted ecosystem *structure* or *function*, or the *services* and associated *benefits* to human wellbeing (Fig. 1). Two aspects are important here: First, the measure can be provided either "*in-kind*" (i.e., same ecosystem *structure* as the damaged resource and therefore also the same associated *function, services,* and *benefits*) or "*out-of-kind*" (an entirely or partially different ecosystem *structure, function, service,* or *benefit*). Second, the measures can be undertaken in close proximity to the damage site ("*on-site*") or at a different and more distant location ("*off-site*"), where the latter implies that any potential benefits generated by the measure – including benefits that may be similar or somewhat different – will not reach those individuals affected by the loss. Box 1 provides examples to illustrate the range of impacts and the types of compensation included in our definition (see also Bull et al., 2015).

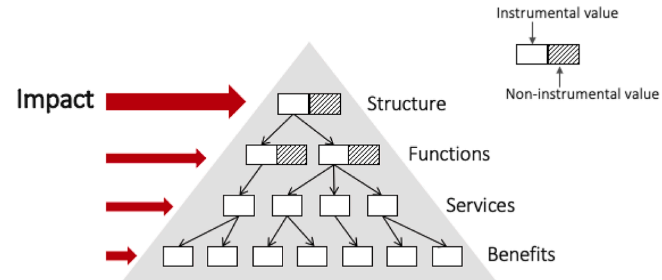

Fig. 1. Conceptual overview of compensable values. Adaptation of the ecosystem services cascade model to include instrumental values (symbolized by white boxes) and non-instrumental values in ecosystem structure and function (symbolized by shaded boxes). Our adaptation helps to better understand the negative impacts from environmental damage (losses), which subsequently ensures a more comprehensive assessment of compensation need (gains). Negative impacts associated with physical development are most likely to occur on the structural level, as symbolized by the thicker upper arrow.

Box 1. Non-exhaustive examples of the scope of "environmental compensation" as defined in the framework. *A hypothetical construction project leading to loss or deterioration of habitat and indirect local effects associated with the project.*

Examples of likely damages	*Examples of relevant environmental compensation projects*
Permanent impacts	The following projects may be relevant *on-site* or *off-site*:
• Loss of habitat, here primarily identified as migratory bird habitat	• Restoration or rehabilitation of lost habitat type ("*in-kind*")
• Closure of a recreational access point to a popular park/reserve	• Protection of migratory bird habitat elsewhere that is otherwise threatened
• Increased noise levels associated with road use impairs ways in which the area can be used by people and wildlife	• Predator control or regulatory measures to reduce total migratory bird mortality
Temporary impacts	• Creation of alternative migratory bird habitat
• Nuisances such as increased noise levels and dust during construction	• Construction of new recreational access points
• Trail closure during construction	• Improvement of other existing recreational trails/facilities
	• Establishment of a "quiet" reserve that restricts noise levels
	• Other projects that improve or protect similar resources that the public accepts as compensation for those lost ("*out-of-kind*")

3. A suggested framework

Compensation planning typically involves four steps: assessing damage, assessing compensation needs, selecting compensation options, and evaluating outcomes (Fig. 2). Our framework provides conceptual guidance to support these steps, which are described in Sections 3.1 to 3.4.

3.1. Assessing damage (Step 1)

The first step of the framework uses the cascade model as a roadmap to describe potential damage pathways. The approach "casts the net wide" in identifying potentially relevant benefits generated by a given ecosystem and how they may be impacted (see e.g., Olander et al., 2015) (Fig. 3). Pressures impacting the *structure* level (e.g. habitat deterioration or loss) are generally expected to lead to subsequent loss of all connected *functions*, *services* and *benefits* via 'cascading effects' (red boxes in Fig. 3a). In addition, in some cases, impacts at lower levels of the cascade may only occur when they are directly connected via a damage pathway at that level (red and green boxes in Fig. 3b-d). Last, impacts on benefits may also occur independent of the cascade model (Fig. 3e). The loss of these cascade-independent benefits, while not directly linked to the affected habitat, are nonetheless connected to coinciding human activities and thus relevant in a damage assessment (see Section 4.1 for an example involving eelgrass).

3.2. Identifying compensation needs (Step 2)

The second step involves identifying compensation needs based on the cascade model and, if relevant, modifying these to meet any stakeholder objectives. Compensation needs are highlighted via the cascade model by an analysis to identify gaps, where negative impacts may be either full or partial (Fig. 4). Fig. 4a illustrates a case when negative impacts at the *structure* level lead to full loss in all subsequent levels, suggesting that compensation aimed at the *structure* level – via e.g. creation or restoration of habitat – would compensate all linked losses to *functions, services* and *benefits.* Alternatively, impacts on ecosystem *function(s)* affect only a portion of the subsequent 'downstream' impacts, suggesting less extensive compensation needs (Fig. 4b), e.g., impacts to a migratory route that do not significantly impact a local habitat structure. Note that this process can be, but is not restricted to, establishing a compensation objective based on "No Net Loss of Biodiversity and Ecosystem Services" (see e.g., EC, 2007; Maron et al., 2018).

Since compensation needs are also a function of local context, this step importantly provides flexibility for decision-makers regarding compensation needs suggested by the cascade model: Fig. 4b and c have the same identified damages, with impacts on the ecosystem function level. The final compensation needs for (b) suggest full compensation for all affected ecosystem services, whereas in (c) a subset of the affected ecosystem services are only partially compensated. The yellow boxes reflect increased substitution possibilities associated with the service/benefit levels. In this case, two of the three damaged ecosystem services are fully compensated (green) and the third is partially compensated (yellow). A partial compensation need is also identified for a fourth ecosystem service, which represents a modification to balance the fact that full compensation for all three damaged ecosystem services was not possible (or perhaps desired).

The final compensation needs can meet stakeholder objectives at two different levels: first, in relation to overarching objectives, such as ensuring consistency with strategic planning, environmental goals or legal obligations (e.g., halting the loss of biodiversity, interests of future generations, reducing environmental impacts of infrastructure, etc); and second, on a more local level in relation to specific and normative principles that consider the needs of affected individuals in the current generation (see e.g., McKenzie et al., 2011; Scholte et al., 2016*)*. The cascade model offers a language for discussion of these general approaches and viewpoints – including how and when they may conflict – which allows for a more fruitful integration of compensation needs with stakeholder objectives (see also Sonter et al., 2020).

3.3. Selecting compensation (Step 3)

In the third step, the final compensation needs are examined in relation to a hierarchy of preferred options, where the cascade model is used to support a gaps analysis and identify the preferred compensation option(s) (Fig. 5). The hierarchy adheres to the principle that those affected by damage should benefit from the compensation, and prioritizes on-site compensation. However, it also considers options related to resource type (*in-kind/out-of-kind)* and resource location (*on-site/off-site*). Although the "nearby and similar" principle for compensation selection is well established in the literature (BBOP 2012), our framework is designed to be applicable across a variety of compensatory contexts, including situations where residual losses are unavoidable; *on-site* and/or *in-kind* are not technically or practically feasible; a regulatory scheme has certain requirements (e.g., *out-of-kind* must be considered); or compensation *in some form* must be obtained from a responsible party for de facto losses (*ex post* schemes).

Since the final compensation project may consist of several individual measures, we distinguish between primary measures, which are the principal focus, and complementary measures, which strive to fulfill any compensation needs not met by the primary measure (including possible equity concerns) using additional *out-of-kind* approaches. We present the hierarchy of preferred compensation options below and then discuss considerations for making a final compensation selection.

First option: Primary measure = *in-kind/on-site*

The framework places an emphasis on first the resource type (*in-kind* measures are preferred over *out-of-kind* measures), and second the resource location (*on-site* measures are preferred over *off-site* measures). This is preferred because:

In-kind measures, provided they are successful, are the only way to address possible non-instrumental values, linked e.g. to biodiversity, given an assumption that trade-offs between non-instrumental values are not an option (i.e., *in-kind/on-site* compensation is by definition linked to that particular structure/function). Further, *in-kind* measures, if successful, provide more reliable compensation gains as they avoid ecosystem complexities by not having to rely on uncertain links in the cascade model between the upper levels (structure/function) and the (downstream) levels related to wellbeing. As a consequence, they tend to require fewer measures to achieve a compensation goal.

On-site measures are more likely to deliver benefits to those individuals that are affected by the damage, since all structure-dependent benefits are compensated for.

If successfully implemented and correctly scaled, the first option meets all compensation needs identified by the cascade model and thus requires no complementary measures (with the possible exception of cascade-independent impacts on benefits, Fig. 3e).

Second option: Primary measure = *in-kind/off-site*

If *in-kind* compensation is not feasible *on-site* (due to e.g. lack of suitable locations), the second option is *in-kind* compensation *off-site*. The selected *off-site* location should exhibit suitable living conditions for the structure subject to compensation and should be as close as possible to the damaged site (as in First option above). However, as *off-site* measures will not compensate the local impacts, additional complementary (*out-of-kind*) measures will be warranted *on-site* (i.e., the second option does not, by definition, meet compensation needs as well as the first option).

Last option: Primary measure = *out-of-kind*

If *in-kind* compensation is not feasible within the relevant spatial context, the last option is to use several *out-of-kind* measures either *on-site* or *off-site*. Although this will rarely ensure the same level of compensation as the first or second options, we suggest a key guiding principle to optimize the outcome: a preference for measures aimed as high up on the cascade levels as possible, since these are more likely to capture any possible non-instrumental values, to lead to a broader range of subsequent benefits and to require fewer measures to achieve a given compensation goal. Note that this suggests at least the *function* level, since *structure* is not relevant when using *out-of-kind*. We emphasize, however, that the last option will not fully meet the principle that those affected by the damage should benefit from the compensation. This is obvious when measures take place *off-site*, but even if they are *on-site* the population receiving the gains are, by definition, receiving different benefits than those that were lost, since the compensation is provided *out-of-kind*. Further, the last option entails a high risk of not meeting compensation needs related to losses of biodiversity. In part because of

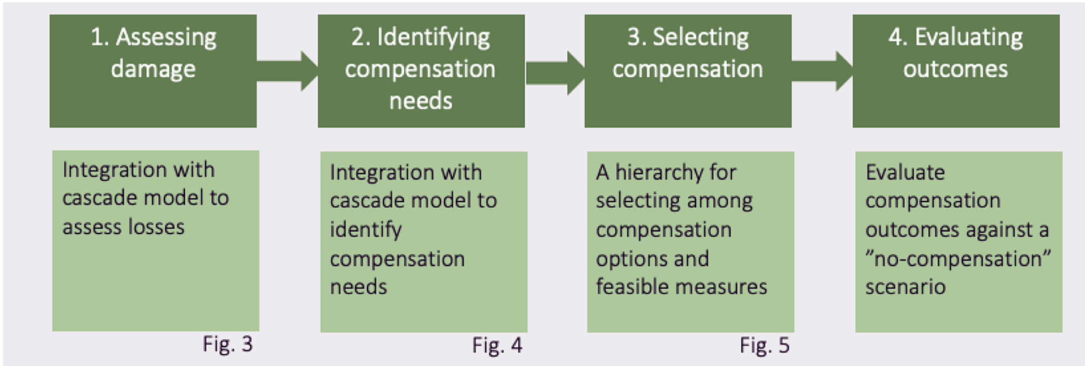

Fig. 2. Overview of framework. Lower row specifies the framework's contribution to each of the four steps typically found in a compensation assessment. Sections 3.1–3.4 and Figs. 3–5 provide details.

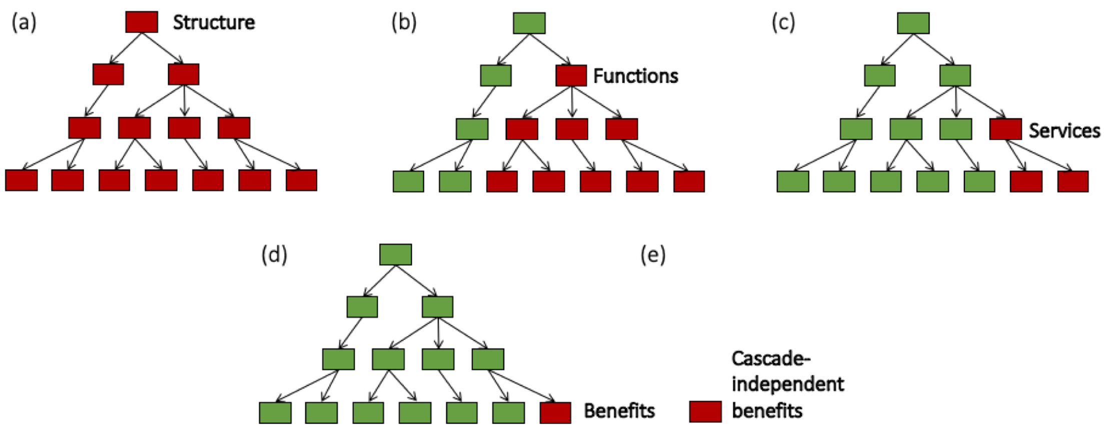

Fig. 3. Assessing damage using the cascade model (Step 1). Possible pathways include negative impact on *structure*, causing subsequent impact to all underlying levels via 'cascading effects' (red boxes in (a)). It may also impact on *function(s)* level (b) or *ecosystem service(s)* level (c), causing impact to these levels and subsequent levels via 'cascading effects.' Finally, it may impact on the human benefit level (d) or other relevant but cascade-independent benefits (e).

these drawbacks some policies and guidelines advise against (or restrict) the use of *out-of-kind* compensation. However, the option remains widely discussed (see e.g., Habib et al., 2013; Bull et al., 2015). Therefore, we include it to provide decision-makers with a transparent approach for understanding the consequences and trade-offs between compensation options.

While complementary measures will certainly be needed under the second option, they may even be warranted under all three compensation options, if there are cascade-independent impacts on benefits (Fig. 3e). They may also be warranted to address interim losses that can occur between the time when the damage occurs and the compensation is fully implemented (Cole, 2011; Bull et al., 2014) or to address stakeholder objectives or vulnerable groups.

Final compensation selection

The preferred compensation options (Fig. 5) provide a basis for a final compensation selection, which should consider stakeholder objectives (step 2) and the trade-offs between options in the hierarchy. For example, ecological risk trade-offs exist generally between the three options: low risk with in-*kind/on-site* compensation; higher risk with in-*kind/off-site*; highest risk with *out-of-kind*. In other cases, legal trade-offs may exist when developing local compensation rules, such as whether to allow *out-of-kind* compensation. Finally, there may be case-specific trade-offs such as a decision between (a) *out-of-kind* but *on-site* and (b) *in-kind* but *off-site*. In such cases, the framework's process for modifying compensation needs (step 2) can guide decision makers: for example, all else equal (a) may be more attractive if those individuals affected by the damage are part of a vulnerable group that require extra consideration; alternatively (b) may be more attractive if emphasis is placed on no net loss. Further, it could include an overview of distributional effects to determine who is affected, who benefits, and whether impacts may affect vulnerable groups disproportionately (e.g., socioeconomically disadvantaged, elderly, children, etc).

Finally, if compensation assessment is part of the permission process itself,[5] the framework allows for decision-makers to consider an "off-ramp" option (dotted arrow in Fig. 5). For example, after considering all three preferred options, some decision makers may still be uncomfortable with a 'compensation solution' (or may be legally required to consider other solutions). In this case the offramp offers avoidance rather than compensation, i.e., reconsiders the suitability of the impact-causing project. Such an outcome may occur if the framework makes clear that compensation of residual losses is either not technically possible, not preferred by affected individuals, limited by local guidelines, or simply turns out to be riskier than originally envisioned. Note that the offramp option is not relevant if the permission process is separate from compensation assessment (as suggested in Sweden; Swedish EPA, 2016).

3.4. *Evaluating outcomes (Step 4)*

A post-project evaluation should compare the compensation outcome(s) to the final compensation needs (Fig. 4) after a specified

[5] When compensation is required as part of the permitting process, then all options are on the table, including *out-of-kind*, which may be the only feasible alternative.

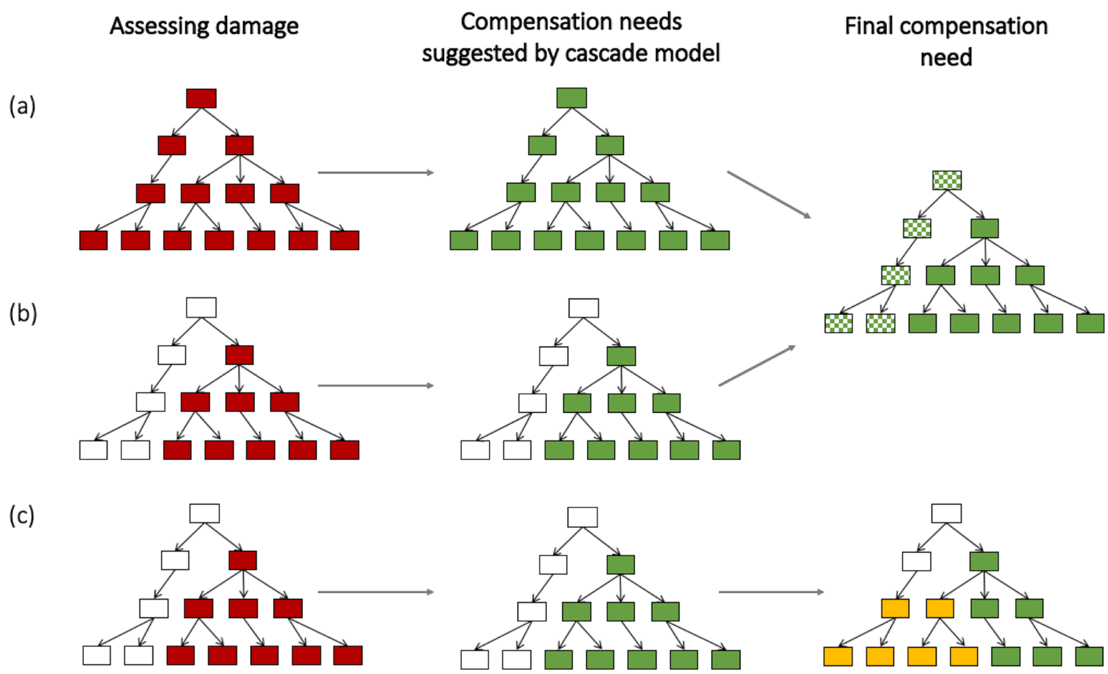

Fig. 4. Identifying compensation needs using the cascade model (Step 2). Potential outcomes for compensation needs suggested by the cascade model: In outcome (a), comprehensive compensation needs are suggested since impact on the *structure* level leads to complete loss of all subsequent levels via 'cascading effects': *function, service,* and *benefits* (Note: green boxes in the middle are identical to the green and hashed boxes in the last column). Fewer green boxes in (b) suggests less extensive compensation needs suggested by the cascade model since the impact only affects some of the *functions* and hence a portion of the downstream levels (green boxes in the last column). Finally, the yellow boxes in (c) suggest the possibility to modify compensation needs suggested by the cascade model to meet stakeholder objectives (see text). Note both (a) and (b) assume no modification of the compensation needs suggested by cascade model and (c) assumes modification occurs on the ecosystem service and benefit levels.

time period, and against a "no compensation" scenario. This evaluation, and subsequent adaptive management, can also be guided by the cascade model, which can help identify parsimonious follow-up indicators to determine whether the compensation objective is met, i.e., cascade losses are matched by cascade gains. Useful indicators can save resources for both the responsible polluter (to evaluate their commitments) and the authorities (to ensure transparency). By tracing links in the cascade model attention can be focused on the indicators with the greatest potential bearing on outcomes that matter the most – including underlying levels of the cascade and/or the benefits provided. In conjunction with local legal requirements, such evaluation may provide the basis for additional compensation requirements, penalties, contingency plans and/or other measures to address possible failures.

4. Application: compensation for habitat loss in a coastal area

The variety of compensatory approaches that the framework can handle, and the important policy issues that are raised by this work, are illustrated by a hypothetical case involving the loss of eelgrass meadows (*Zostera marina* L.) due to construction of a marina along the Swedish west coast. Eelgrass is a seagrass species of temperate waters with importance for biodiversity and ecosystem services (Orth et al., 2006; Barbier et al., 2010). We choose this example because the eelgrass ecosystem is well-studied (Table 2) and methods for eelgrass restoration are well developed (e.g. Fonseca et al., 1998; Short et al., 2000; Orth et al., 2012; Moksnes et al., 2016). For example, it is regularly used for environmental compensation in the US (e.g. NOAA, 2014). As the proposed framework is still novel, real-world illustrations of its approach do not yet exist. Therefore, in order to show how managers could apply the concepts in real and potentially complex policy situations, we generate hypothetical scenarios that motivate three complete compensation options based on the framework's hierarchy (Fig. 5). We discuss key considerations for selecting from among these options, any of which could be feasible in a given location and context. The example is relevant in Sweden, where avoiding losses of eelgrass meadows, and preferably enhancing them, is motivated both by the EU Biodiversity Strategy (Table 1) and status assessments in relation to the EU Marine Strategy Framework Directive and Water Framework Directive. According to Swedish environmental legislation, compensatory measures should be considered in the case of unavoidable damages to habitats of importance for biodiversity and ecosystem services. Further, the Swedish Agency for Marine and Water Management has published guidelines and methods for eelgrass restoration, which they suggest could be applied to cases involving environmental compensation as a tool to protect or enhance these habitats (Moksnes et al., 2016).

4.1. Assessing damage

In western Sweden, eelgrass grows on soft substrates in shallow waters, where it contributes to several ecosystem functions by effects on the physical, chemical and biological environment. This, in turn, results in a number of ecosystem services and benefits, of which the most well-documented are illustrated in Table 2 and Fig. 6 (Rönnbäck et al., 2007; Cole and Moksnes, 2016; Nordlund et al., 2016). The knowledge base for the eelgrass ecosystem and the benefits they provide along the Swedish west coast is well-documented (Rönnbäck et al., 2007; Stål et al., 2008; Cole and Moksnes, 2016; Röhr et al., 2018).

In our example, we assume that an eelgrass meadow is lost permanently due to marina construction and, as a result, all eelgrass *functions*, *services* and *benefits* are also lost permanently (Table 2; Fig. 6(1)). For example, the loss of the eelgrass function "dampening of waves" leads to loss of services "decreased beach erosion" and "decreased sediment resuspension" and, ultimately, to loss of benefits associated with beach recreation (due to decreased visibility affecting users). By linking ecosystems and the subsequent benefits – including the spatial scale over which they occur – the cascade model can help avoid the problem of

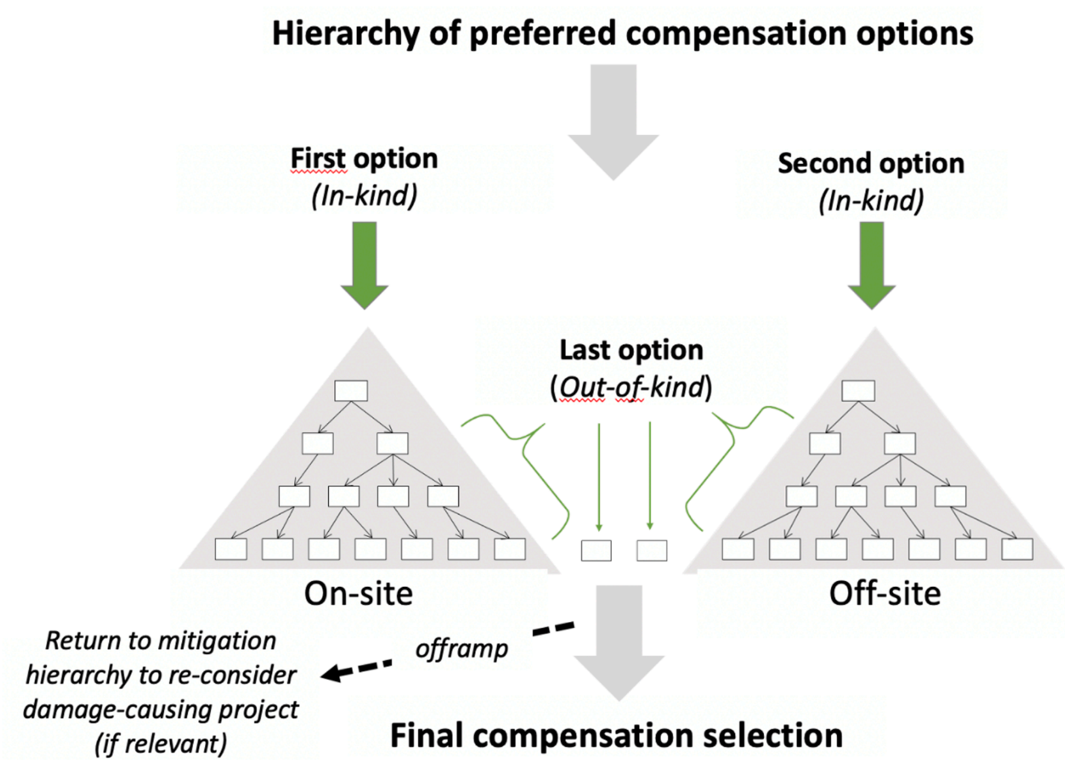

Fig. 5. Framework's hierarchy for selecting compensation options (Step 3). Assuming those affected by damage should benefit from the compensation, the framework's hierarchy of preferred compensation options suggests: *on-site* compensation aimed *in-kind* at the structure level. If not feasible, a second option is *in-kind* compensation *off-site* (provided suitable conditions at compensation site) together with complementary measures *on-site* to address local non-compensated impacts. If the second option is not feasible, the last option relies on *out-of-kind* measures, preferably aimed as high up on the cascade levels as possible. All options may require additional complementary measures in order to address possible cascade-independent impacts on benefits (white boxes outside the cascade pyramid) or to address interim losses. Complementary measures are, by the framework's definition, *out-of-kind.* Final compensation selection depends on stakeholder objectives and considerations of the trade-offs between options. If compensation is part of the permitting process an offramp affords decision-makers an alternative to a 'compensation solution'.

double-counting impacts, i.e., inadvertently capturing the same value associated with an impact multiple times (see example under Sec 4.2).

In addition to losses related to the eelgrass meadow, we assume impacts to some cascade-independent benefits (see Fig. 6(2)). For example, marina construction activity may permanently close a recreational access point, which would lead to recreation losses; alternatively, the noise, dust or other disturbance may diminish the recreational experience for local users (cf. Box 1). The loss of these benefits, while not directly linked to the affected habitat, are nonetheless connected to coinciding human activities and thus relevant in a damage assessment.

The metrics chosen in the damage assessment are a foundation for the compensation assessment and, in some cases involving complementary compensation, several different metrics may be required. If eelgrass compensation will be *in-kind*, the damage may be expressed in units of habitat area (i.e. hectares of lost eelgrass). In other cases, an eelgrass ecosystem *function* or *service* may be expressed as e.g. kg of lost cod production or tons of released carbon (Table 2). In some cases, monetary metrics may be used to assess the change in wellbeing associated with an ecosystem benefit, e.g., willingness to pay for a recreational beach visit (see e.g., Lipton et al., 2018; US DOI, 2019).

4.2. Identifying compensation needs

Our default example assumes a goal of "No Net Loss of biodiversity and ecosystem services" (see Section 3.2). Relying on the cascade model compensation needs will, under this scenario, cover the full range of negative impacts (i.e., convert all red boxes in Fig. 6 to green "compensated" boxes in Fig. 7). Alternatively, the stakeholder process could potentially lead to identification of other final compensation needs (see Section 3.3). Importantly, in the example of eelgrass meadows, its associated benefits occur on different spatial scales (local, regional, global), which may affect final compensation needs, including the need for complementary measures. Further, the valuation of losses and gains can depend on location, and hence affect the type and extent of compensation needs (see Table 2 and examples below).

Given any of these objectives, the ensuing compensation measures may aim to restore eelgrass habitat *structure*, replace ecosystem *functions* or improve *benefits*. As an example, juvenile fish production (*service*) from an eelgrass bed benefits both recreational fishing (improved recreational experience from higher catches) and commercial fishers (increased income from higher catches) on a regional level. The cascade model structure focusing on *final* beneficiaries (instead of the *intermediate* production of fish) identifies these two distinct user groups to whom separate and "additive" benefits accrue, which can be reflected in the compensation needs.[6] The cascade model can also help stakeholders identify measures that provide *multiple* benefits – all else equal, such measures represent more attractive compensation options. For example, eelgrass restoration in one location may provide recreational benefits for both cod fishing and swimming, while the same restoration in an alternative location where habitat availability is not limiting for the cod production, would predominantly benefit swimming.

[6] We acknowledge that environmental compensation schemes typically cover recreational impacts, such as those to recreational fishers but income losses to commercial fisheries are addressed through other liability schemes (Lipton et al. 2018; US DOI 2019).

Table 2
Illustration of the ecosystem services cascade model applied to eelgrass: Examples of *functions, ecosystem services,* and *benefits* provided by eelgrass habitat structure. The last two columns show examples of metrics for assessing damage and compensation and the scale at which benefits are experienced. Benefits that occur on different spatial scales (local, regional, global) can affect the net impact on wellbeing and thus compensation scaling (see examples in text).

Functions (examples)	Services (examples)	Benefits (examples)	Possible metric[1] for assessing damage/compensation (examples)	Benefit scale
Habitat for plants and animals	Maintenance of high production and biodiversity	Opportunities for research, education, recreation,	Diversity and abundance of species	Regional
	High juvenile production of fish and crustaceans	Commercial fish catch, improved recreational fishing	No. of juvenile cod; monetary value	Regional[2]
Dampening of waves, sediment stabilization	Decreased beach erosion	Improved recreational experience (beachgoing)	Sediment transport; monetary value	Very local
	Decreased resuspension and clearer water	Improved recreational experience (swimming)	Turbidity, water clarity (e.g. Secchi depth); monetary value	Local
Sequestration of organic material	Removal and long-term storage of nutrients	Decreased damages from eutrophication on society	Tons of nutrients released from sediment and sequestered per year; monetary value	Regional
	Removal and long-term storage of carbon	Decreased damages from climate change	Tons of carbon released from sediment and sequestered per year; monetary value	Global

[1] Metrics may focus on measuring the biophysical change directly or on monetary metrics that value the change in wellbeing associated with the loss or gain of benefits (for e.g., beach recreation, commercial fish catch, recreational fishing, climate mitigation, etc.).
[2] Regional benefits may accrue in this case to both commercial and recreational fishers (see example in text).

4.3. Selecting compensation

Below we describe three preferred compensation options (in the order suggested by the hierarchy) for the eelgrass loss based on the framework's principles.

4.3.1. First option: In kind/on-site

The first option (*in-kind, on-site*) suggests restoration of an eelgrass meadow at the damage site. If the restoration is successful, all losses of ecosystem *functions, services* and *benefits* will be compensated for (green boxes, Fig. 7a(1)). However, since it takes time for a restored meadow to provide the same services as a natural meadow (up to 10 years or more; see e.g. Marbá et al., 2015), there will be an interim loss[7], which suggests the need for additional complementary compensation. This can be provided by simply restoring a larger eelgrass area than was lost. In practice, this is often achieved by using habitat scalars (i.e., suggested habitat area ratios of "loss-to-gain"). The proposed policy for eelgrass in Sweden suggests restoring 30% larger eelgrass meadow than the one lost, if restoration is started in the same year as the damage occurs (Moksnes et al., 2016), while eelgrass mitigation scalars in California explicitly account for the risk of failure (NOAA 2014).

The first option has the advantage that ecosystem *functions* and *services* that provide local benefits (e.g., dampening of waves and decreased wave erosion) are more likely to reach those affected by the damage. Further, it can be scaled using a single metric (e.g., habitat area), which can facilitate assessing, scaling, and evaluating compensation. However, in this example, we assume that construction activity affects recreational benefits that are independent of eelgrass structure, which therefore requires additional complementary measures (e.g., improve beach access nearby with e.g., boardwalks, stairs, or other attributes valued by beachgoers, Fig. 7a(2)).

4.3.2. Second option: in-kind/off-site

Since the first option may not be feasible due to a lack of suitable sites or environmental conditions for restoration (Fonseca et al., 1998; Moksnes et al., 2018), the second option suggests *in-kind/off-site* – assuming a good compensation site can be found (Fig. 7b(1)). Recreating a similar eelgrass meadow at a favorable *off-site* location would compensate for the original loss by generating the same types of ecosystem *functions* and *benefits* as the first option, but some functions will only benefit those near the compensation site. For example, the ability of eelgrass to stabilize sediment, which decreases sediment resuspension and beach erosion and improves beach recreation, acts on a local scale (see Table 2, Fig. 6). If such benefits were critical at the damaged site, then *off-site* compensation, even if only a few hundred meters away, will not prevent e.g. beach erosion at the site where it is needed. Thus, ecosystem services related to stabilization of sediment will never be compensated for with an *off-site* measure. In contrast, carbon removal provides benefits on a global scale and is independent of location. As the distance between the compensation site and the damage site increases, more and more benefits will not reach the damage site, which argues for (additional) complementary measures to ensure full compensation.

In the *in-kind/off-site* example illustrated in Fig. 7b, the nutrient removal from the restored meadow at the compensation site is considered to be sufficiently close to provide full benefits at the damage site, the enhanced production of fish and biodiversity from the meadow will provide some benefits at the damage site, but will not compensate all losses, whereas the loss of sediment stabilization at the damage site will receive no compensation from the restored meadow. To compensate these local losses, one could suggest an (additional) complementary measure aimed at the ecosystem *function* level: construction of a wave breaker of rocks at the damage site (Fig. 7b(2)). This (*out-of-kind*) measure is expected to dampen waves and stabilize the sediment and thereby fully compensate the lost benefits related to sediment resuspension and beach erosion. The submerged part of the rocks may be colonized by algae and animals over time and thereby could contribute to improved biodiversity and fish production at the damaged site. However, since the hard substrate produces a different biological community compared to eelgrass, it will only provide partial compensation toward these services. Although the combination of *off-site* restoration helps to provide reasonably complete compensation, the second option will not fully reach the no net loss objective achieved by the first option. Finally, complementary measures to address loss of cascade-independent benefits, as in the first option (improve beach access, Fig. 7b(3)).

We emphasize that *off-site* compensation should consider the environmental and social conditions across sites. For example, the eelgrass *structure* may differ in *functions* at the compensation site (e.g., different production, shoot density, canopy height, areal extent, etc.), which can

[7] All else equal, interim losses suggest that a permanent loss requires greater compensation than a temporary loss (e.g., boat propeller injuries to eelgrass may recover over time whereas marina construction impacts are permanent). Further, an interim loss can be avoided if the compensation site is constructed prior to the loss, such that there is no interruption in the delivery of services.

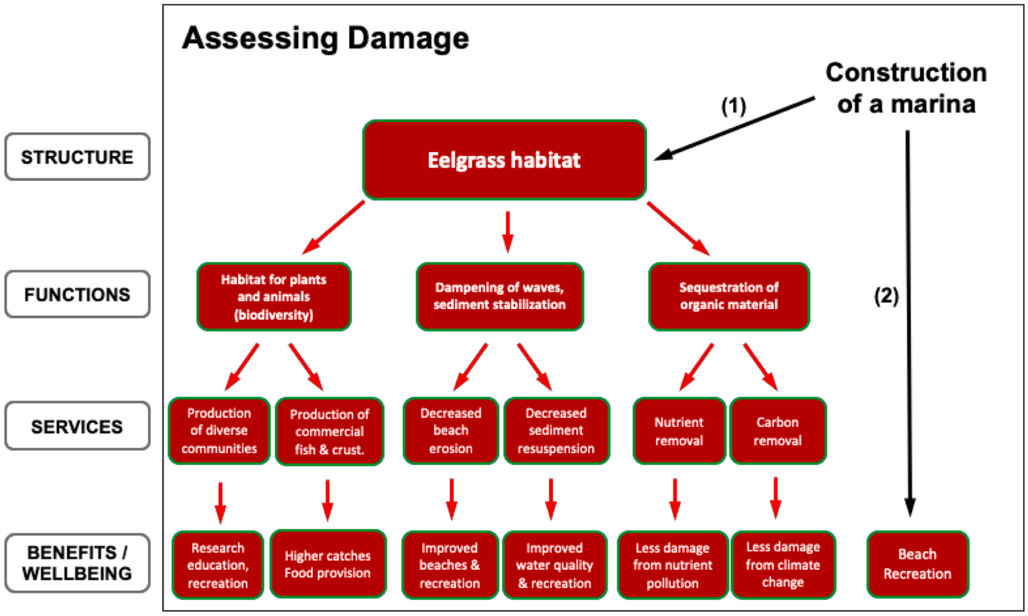

Fig. 6. Assessing damage using the cascade model: eelgrass illustration. Assessing damage from marina construction via the framework's cascade model. The loss of an eelgrass meadow (1) and the loss of the physical *structure* of eelgrass causes the loss of ecosystem *functions*, *services* and associated *benefits* (see Table 2). The restricted access and noise disturbance impacts during construction affects nearby beach recreation (2), which are independent of the impacts to eelgrass *structure*.

affect provision of *services*. Further, the value of provided *services* may differ depending on spatial conditions; in general, an eelgrass bed will have a higher value if the ecosystem function is "locally limiting" for the production of the *service* and/or if the *benefit* is in short supply or high demand (Cole and Moksnes 2016). For example, if nursery habitats for juvenile fish are in short supply in an area and limiting for the recruitment, the eelgrass bed will have a higher value than in an area with a surplus of nursery habitats (Sundblad et al., 2014), highlighting the importance of assessing the spatial extent. Such differences can be accounted for in compensation by increasing the scale of *in-kind* compensation (e.g., restore a larger area) or using additional *out-of-kind* compensation (see below).

4.3.3. Last option: out-of-kind

There may be local situations where *in-kind* compensation for eelgrass is not possible due to lack of knowledge, lack of tested methods, or lack of suitable sites within a reasonable distance from the damaged site. In these scenarios, *out-of-kind* compensation (either *on* or *off-site*) may be the only available alternative, even if it cannot fully achieve the compensation objective.

Out-of-kind compensation requires creativity in re-creating similar benefits to those that were lost. The benefits may be linked to different ecosystem *structures* that provide similar *benefits* or may be entirely independent of structure and instead be based on human-designed substitutes. However, such measures admittedly contribute to additional physical alterations in the coastal environment which should be considered. *Out-of-kind* measures may only be possible in compensation schemes that allow for flexibility in design (Bull et al., 2015); further, it assumes that the public values the loss and gain equally, even though the characteristics of both may differ significantly.

An exhaustive list of potential *out-of-kind* measures for eelgrass damages is beyond the scope of this illustration, and therefore not included in Fig. 7. However, the cascade model in Fig. 6 can provide a structure to help identify relevant approaches. For example, *out-of-kind* compensation could target the ecosystem *function* level by creating artificial reefs, which provide habitat for plants and animals that rely on eelgrass for substrate; or focus on creating or restoring coastal wetlands to sequester nutrients. Another approach could be to focus on relevant benefits by e.g., improving access to beaches or enhancing valued attributes like showers, boardwalks, more frequent seaweed clean up, etc.

4.4. Evaluating outcomes

At the overarching level an evaluation of compensation outcomes in the eelgrass example would address the question: *"Have we reached no net loss?"* At the more specific level, measurable goal formulation is critical. Further, field monitoring should account for the fact that some ecosystem services provided by eelgrass will require many years after restoration to reach the levels provided in established natural meadows. Guidelines elsewhere recommend that restored meadows be monitored for 5–10 years before evaluating results, and should be compared to relevant nearby reference sites, which can help model the natural variation in areal extent and provision of ecosystem services (see examples by Fonseca et al. (1998); NOAA (2014); Moksnes et al. (2016)). The cascade model supports evaluation by helping to specify which ecosystem services are expected from the compensation measures (e.g. biodiversity, abundance of juvenile fish, water clarity, carbon and nutrient content in the eelgrass sediment), and which should be the focus of follow-up monitoring.

5. Discussion

Existing frameworks for compensation face a challenge in balancing two goals: *flexibility* to suit the myriad of compensatory schemes found globally, versus *consistency* to ensure polluters' environmental liability is measured consistently and fairly. Our review suggests that the scope of compensatory schemes varies: some aim to offset environmental loss in relation to its impact on human wellbeing while others focus on offsetting biophysical changes regardless of whether they measurably affect humans (Table 1). The former may be viewed as reflecting nature's instrumental values for humans, whereas the latter may reflect its non-instrumental values, or possibly a precautionary approach for safeguarding human wellbeing by recognizing that full information required to link ecosystem structure to services and benefits may never exist. This variation in starting points – together with a lack of data to capture instrumental values and the conceptual and practical challenges of integrating non-instrumental values – makes it difficult to provide a

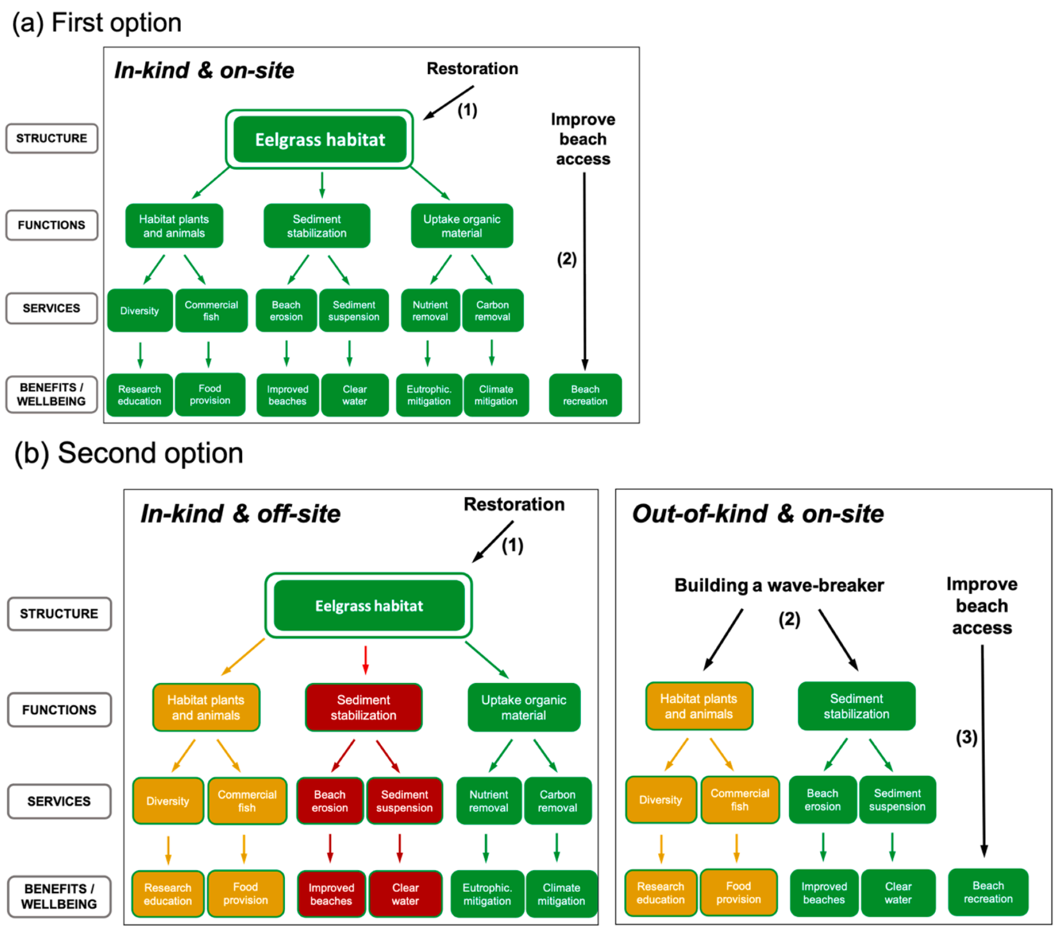

Fig. 7. Considering preferred compensation options using the cascade model: eelgrass illustration. Two alternative compensation options generated by the framework to address eelgrass impacts: The first option (a) includes two components: a(1) restoration of eelgrass meadow at the damage site (*in-kind, on-site*) to restore *structure* and subsequent *functions, services,* and *benefits* and a(2) improve beach access to address loss of *benefits* that are independent of eelgrass habitat. The second option (b) should be considered when the first option is not feasible and contains three components: b(1) restoration of an eelgrass meadow at a close-by suitable site (*in-kind, off-site*) that restores similar *functions* and subsequent *services* and *benefits*, but some of them only at the compensation site, not the impacted site. The example illustrates a case where one benefit fully reaches the damage site (green box), one partially reaches the damage site (yellow boxes), and one does not (red boxes). Therefore, complementary compensation (*on-site/out-of-kind*) b(2) could generate a similar ecosystem function (e.g., building a wave breaker of rocks). Note that b(2) fully compensates one ecosystem service (green boxes) and partly compensates another (yellow boxes) since the hard substrate produces a different community compared to eelgrass. Together with the *off-site* compensation of this service b(1), the benefits can be considered compensated. Finally, as in the first option, recreation enhancement addresses loss of benefits that are independent of eelgrass habitat b(3). Several other considerations are relevant before making a final selection of compensation, see text.

framework that can be applied consistently across compensation schemes with different needs (see also e.g., Bull et al., 2014). Even when data are available to populate the existing models, some compensation assessments still leave relevant values un-addressed, as underscored by Moilanen and Kotiaho (2018), who emphasize the need for more "systematic and transparent" approaches to compensation design (p. 113).

Our compensation framework attempts to address these challenges by combining a structure founded on the science of ecosystem services with the flexibility needed to make it operational in the real world. The beneficiaries of a flexible framework include local decision-makers (on a policy, legal, or management level), but importantly also the ecosystem and those who are dependent on its benefits. Even developers can benefit through a more predictable and transparent process that clearly defines compensation requirements based on the robust cascade model, which makes evident the costs related to damaging biodiversity and ecosystem services.

The framework is designed to work across a variety of compensatory schemes, rather than being tied to a specific goal (except the general policy objective of halting biodiversity loss). For example, the eelgrass case assumed compensation needs based on "No Net Loss of Biodiversity and Ecosystem Services," as per the EU Biodiversity Strategy. In contrast, the US's Natural Resource Damage Assessment (NRDA) goal is to "*make the public whole;*" but this too could be accommodated by focusing on the *services/benefits* levels of the cascade model (see Table 1). The expanding scope of offsets today, from a primary emphasis on addressing biophysical impacts to a wider scope including the benefits these systems provide, makes the framework's comprehensive focus on *all* levels of the cascade model particularly salient (Tallis et al., 2015; Maron et al., 2016; Griffiths et al., 2019).

We suggest a method for identifying habitat-based compensation needs and propose a hierarchy for selecting among suitable compensation options. At the top of the hierarchy is a suggestion for *in-kind* compensation aimed at the ecosystem *structure* level. If it can be carried out *on-site,* the benefits of such compensation will reach those affected by the damage. But when it cannot, the framework suggests a second option where *in-kind* compensation is provided *off-site*, together with complementary measures. As a last option, a mixture of *out-of-kind* measures may be considered. Regardless of which of these approaches is taken, the framework recommends complementary measures any time there are cascade-independent impacts on benefits which ensures the inclusion of all relevant human benefits *in addition* to biodiversity (see e.g., Jacob et al., 2016). Finally, the "offramp" affords decision makers (where it is relevant) the option to reconsider the suitability of the damage-causing project if compensation options are considered e.g., infeasible, too risky or inconsistent with legal obligations. However, we emphasize that this option is *not* relevant in regulatory contexts in which the permitting decisions itself is legally divorced from the compensation assessment.

The framework's hierarchy offers a path forward for addressing compensation under two common scenarios: when data are available and when they are not. For example, when data exist (on a detailed or summary level) to describe the relationship between ecosystem structure and subsequent human benefits, the framework can capture relevant instrumental values via the structure of the cascade model, which links ecosystem change to its effects on wellbeing (see eelgrass case in Section 4). Previous authors have noted possibilities for merging the ecosystem services framework into environmental compensation; our approach attempts to operationalize this idea to illuminate the full spectrum of potentially relevant values in the assessment of damages and specification of compensation needs (Olander et al., 2015; Tallis et al., 2015; Jacob et al., 2016; Jones and DiPinto, 2018). The cascade model structure keeps track of losses and gains, which reduces the risk of double-counting benefits and also helps identify compensation options that offer multiple benefits. In addition, it keeps track of the ecosystem services that are expected from compensation, which is useful when evaluating project outcomes (Step 4), particularly in complex cases combining *in-kind* and *out-of-kind* measures.

It is far more common, however, that compensation assessment is conducted in the absence of data linking changes in ecosystem structure to changes in wellbeing. It is here that the framework's integration with the cascade model is particularly helpful, as it leads naturally to the hierarchy's first option: *on-site/in-kind* compensation aimed at the ecosystem *structure* level. Generating gains at the top of the cascade model is the most credible and defensible approach in such cases, as it not only captures instrumental values – since they ultimately depend on ecosystem *structure* – but will, by default, select for compensation gains for which non-instrumental values are most likely to be relevant (e.g., biodiversity). Further, measures aimed at structure reduce exposure to measurement uncertainty associated with the cascade links. Through a primary focus on *structure* (in combination with benefits in the lower levels of the cascade model) our framework addresses a general criticism of compensatory offsetting as an overly-ambitious instrument that fails to incorporate the 'incompatible values' associated with both ecosystem services and biodiversity (Moreno-Mateos et al., 2015; Tallis et al., 2015).

Our framework ensures a replicable process, even when compensation options may be limited, and helps make transparent the fact that compensation gains may be experienced differently by different groups in society (Bull et al., 2015; Levrel et al., 2017). Flexibility in an offsetting context is important since nature's benefits are often diverse, complex and difficult to measure, which makes them less amenable to simple "substitution" of services (Moreno-Mateos et al., 2015; Tallis et al., 2015; Sonter et al., 2020). Moreover, even if substitution (*in-kind/on-site*) were feasible, local or regional strategic objectives – along with legal obligations – may argue for something different. For example, the loss of (1) climate mitigation and (2) recreation from a forest could, in theory, argue for different compensation approaches, where (1) favors fast-growing forests and (2) motivates forest management to select for attributes that are preferred by forest users (e.g. biodiversity, accessible paths, etc). By mapping "who benefits" and "on what scale" our framework makes these trade-offs between compensable values more concrete and visible for stakeholders, which affords decision-makers flexibility in how best to select, motivate, and communicate their compensation selection (Sonter et al., 2020 also emphasize such trade-offs in compensation selection). Consideration of different impacts on wellbeing may also motivate *off-site* and *out-of-kind* approaches, as we discuss below.

Although inspired by the ecosystem services approach suggested by Tallis et al. (2015), our framework differs. Whereas Tallis et al. (2015) considered the entire mitigation hierarchy, the starting point for our approach assumes the existence of residual impacts, despite avoidance and minimization. Where relevant, the framework's offramp option may present an even stronger case for avoidance, if following the framework's four steps still fails to ensure a transparent matching of loss and gain – in such cases, the offramp can be seen as a route back to the first step in the mitigation hierarchy (avoidance).

It is important to note that our framework focuses on compensation for habitat loss or deterioration, including subsequent effects linked to these in terms of ecological functions, ecosystem services and human well-being (for example, it does not handle targeted damage to mobile species). Further, for highly mobile species (including some birds and fish) that are not associated with a single habitat or that alternate between different habitats through their life cycle, restoring the habitat structure will not necessarily lead to the presence of the species in the habitat, since this may depend on other external factors. For instance, a mobile species may not recover even if the habitat is fully restored *off-site* (as under the second option, cf. Section 3.3) if it shows site fidelity or unknown site preferences that prevent it from switching to the restored habitat. In such case, complementary measures for these species may be needed in order to achieve no net loss. In our framework, this could be handled as a cascade-independent impact on benefits, which suggests that mobile species, including their associated ecosystem services, be assessed separately in the damage and compensation assessments (see e.g., Teixeira et al., 2019).

The framework's proposed hierarchy prioritizes *in-kind/on-site* based on an underlying assumption that "those affected by damage should benefit from the compensation". This normative assumption may, under some conditions, be worth examining closer, not least because it has a bearing on the scope for flexibility in compensation selection – a key aspect of our framework. The preference for "similar and nearby" compensation is supported by differing disciplinary approaches, even if regulatory guidance is somewhat ambiguous. For example, ecological equivalence models focus on strict similarity between biophysical loss and subsequent biophysical gain emphasizing *in-kind/on-site* in order to minimize variability between loss and gain (Quetier and Lavorel, 2011; Bezombes et al., 2017; Maron et al., 2018). In contrast, anthropocentric approaches suggest a wider perspective where compensation addresses the benefits that ecosystems provide (Kiesecker et al., 2009; Tallis et al., 2015; Jacob et al., 2016; Maron et al., 2016; Griffiths et al., 2019). Despite the inherent flexibility in these approaches, they generally suggest that the beneficiaries of compensation should be those affected by the damage.[8] In short, both approaches support "similar and nearby", but one eschews flexibility while the other appears to accept it somewhat.

Yet existing guidance on compensation is equivocal on whether *in-kind* and *on-site* compensation is, in fact, preferred. Two oft-cited *ex ante* schemes have an explicit preference for *in-kind* offsets (IFC, 2012; BBOP, 2012). In contrast, *ex post* schemes are somewhat ambiguous. For example, US NRDA guidance covers compensation selection criteria, but none explicitly discusses location or similarity[9] (US OPA 1990, CFR 990.54(a)(1)). Moreover, many of these criteria appear to *maximize* flexibility by emphasizing factors that have a greater bearing on

[8] A slight exception is Griffiths et al. (2018) who suggest that "project affected people be no worse off" but this group includes those affected by the project as well as those who may be exclusively affected by the compensation.

[9] Only the second criteria suggests consideration of whether a project will *"… meet the trustees' goals and objectives in returning the injured natural resources and services to baseline …" (see CFR 990.54(a)(2))* but even this indicates the flexibility afforded the Trustees for determining how to handle the injured resources.

wellbeing (e.g., costs, generation of multiple benefits, public health) than on ecosystem structure and function. During the rule-making process for these criteria, some commenters criticized the lack of a hierarchy favoring *in-kind/on-site*. The agency's response – that a hierarchy is too restrictive – underscores the importance of flexibility in this system, which delegates the question to local decision-makers (USFR 1996, p. 483). The UN Compensation Commission adopted similar criteria, noting that a compensation objective should be "*a context-specific standard,*" suggesting the importance of local flexibility[10] (Payne and Sand, 2011, p. 130; UN 2003). The EU's Liability Directive allows for some flexibility in terms of "type, quality" (EC 2004, Annex II, 1.2.2), but includes more criteria than in the US and UN guidance, including an apparent preference for *on-site* (see "geographical linkage to the damaged site" in EC (2004), Annex II, 1.3.1). These schemes seem to favor, implicitly or explicitly, "similar and nearby" but also retain the option to deviate, leaving one to wonder who is the *designated beneficiary* from the compensation scheme?

The assumed criterion that "those affected by damage should benefit from the compensation" essentially reduces a scheme's flexibility, which could be viewed in light of increasing interest in more flexible schemes, such as habitat banking, despite possible risks (Enetjärn et al., 2015; Bull et al., 2015; see also Kiesecker et al., 2009). This criterion takes a very specific and subjective position in favoring the wellbeing of those affected by damage (the 'victims'). Although it might be defensible from a fairness perspective, this criterion raises questions. For example, how to apply it to an *out-of-kind* measure, which may have uncertain effects on the wellbeing of 'victims'? How to apply it to an *off-site* measure that provides little or no benefit for 'victims,' yet provides a net increase in overall *social* wellbeing? One could argue that the latter measure represents a more efficient way of spending the compensation money recovered from a polluter (see e.g., Cole 2013). The fact that such arguments are rare in a compensation setting could perhaps be traced to a still unresolved conflict between utilitarian and egalitarian views on what compensation should achieve, which might reflect a limited discourse about the ethical underpinnings of compensation (Ives and Bekessy, 2015; Karlsson and Edvardsson Björnberg, 2020). In reality, there may be cases when an alternative criterion could be worth considering, such as "the greatest good for the greatest number" or the wellbeing of 'non-victim' groups.

A example based on our eelgrass illustration highlights the fact that some compensation measures can provide a greater increase in overall wellbeing than others, and could be an underlying motivation for "trading up" (i.e., replacing a damaged habitat with a relatively higher valued one, Habib et al., 2013). In the eelgrass example, the function "carbon sequestration" provides uniform global benefits (reduced climate impacts) while the function "nutrient uptake" provides more local benefits (e.g. improved recreational experience). Depending on the scale of preferences, an eelgrass compensation that provides benefits associated with the reduction of nutrient pollution at site A, generating a value of X may be more favorable in one situation, and eelgrass compensation at site B, generating recreational benefits valued at 2X may be favored in another. Further, net wellbeing could potentially increase even more if option B was less costly (all else equal), which explains the prevalence of the cost criterion in compensation guidelines.

But even if the costs and values generated by two compensation alternatives were equal, one may nonetheless wish to select the measure (s) that benefits a particular user group in society because it may be e.g., underrepresented, vulnerable, or currently lack access to environmental resources (see "system inequality" in Griffiths et al., 2019 as a consideration when assessing an offset's net impacts on wellbeing). Alternatively, a compensation measure aimed at an abundant habitat type for which regional conservation priorities are low may be counterproductive and difficult to motivate (see e.g., Bull et al., 2014). The normative preference for *in-kind/on-site* compensation found in many schemes today suggests that such user groups are ineligible since they happen to live *off-site;* or that local habitats are ineligible for (otherwise prioritized) restoration since they are categorized as *out-of-kind.* Our framework allows decision makers to consider these types of local priorities by modifying the compensation needs generated by the cascade model (step 2) or by considering the distributional consequences of a final compensation selection (step 3). Several aspects could be relevant when considering potentially available options including e.g. planning for green infrastructure, management plans that prioritize a particular habitat or species; political preferences for a particular user group (including future generations), or other factors that affect local compensatory value, such as a resource's scarcity, popularity, or substitute-ability. Modification to include relevant compensation opportunities is consistent with the integration of regional landscape planning perspectives, as suggested by Tallis et al. (2015) (see also Saenz et al., 2013).

A trade-off associated with increased flexibility may entail increased risk of losses to ecosystem's *structure* and *function* (biodiversity), since *off-site* and *out-of-kind* measures will never fully compensate for impacts on these levels at the damage site. Depending on the legal context, excessive flexibility can also conflict with the compensation's effectiveness in preventing damage in the first place. Bull et al. (2014) note that increasing flexibility may turn the "compensation cost" for developers into a simple fine, underplaying the importance of the damaged resource or service. Such an outcome may be avoided, however, if compensation needs are assessed comprehensively, as suggested in our framework.

The hypothetical eelgrass example can be helpful for decision-makers grappling with the appropriate level of compensation, as it highlights an alternative (and equally subjective) assumption about who should benefit from a resource-based compensation. Although the framework's transparency can help identify compensation options that may improve *overall* welfare, final selection nonetheless requires the weighting of one group's wellbeing against another's, including trade-offs across space and time (across generations[11]). In short, even a well-structured and transparent compensation assessment does not remove the need for local decision-makers to take a stand on difficult normative questions associated with whose wellbeing is to be considered and whose wellbeing matters most.[12] Our framework underscores the general need for normative policy guidance, as well as specific clarification on local levels that consider contextual factors. For example, should the "closer is better" principle be followed? And should *out-of-kind* compensation be considered to expand net well-being gains even if doing so reduces the possibilities to compensate biodiversity loss, complicates the compensation assessment, and attracts a larger and more diverse group of stakeholders? We suggest future research be aimed at better understanding the ethical implications and the policy consequences of alternative criteria for *who* should benefit from environmental compensation.

Declaration of Competing Interest

The authors declare that they have no known competing financial

[10] The UN guidance also states that compensation measures should consider a resource's "overall ecological functioning" rather than other (human-use) values, which could be interpreted as emphasizing non-instrumental values (UN 2003).

[11] Note that a compensation project selected today is based in part on the value it generates today. In this sense, it implicitly assumes constant value over time. In reality, some values may increase (suggesting responsible polluters may have "overcompensated" in net) or decrease (suggesting an "under-compensation").

[12] This is similar to the issues of standing and weighting in cost-benefit analysis, see e.g. Johansson and Kriström (2018).

interests or personal relationships that could have appeared to influence the work reported in this paper.

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