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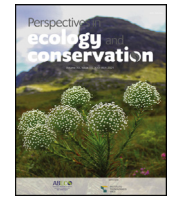

Research Letters

Environmental diversity as a reliable surrogacy strategy of marine biodiversity: A case study of marine mammals

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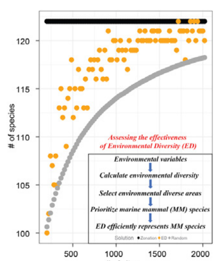
HIGHLIGHTS

- Environmental diversity efficiently represents marine mammal diversity.
- Environmental diversity is an effective abiotic surrogate for biodiversity conservation.
- Environmental variables can be effectively used in marine biodiversity conservation.

GRAPHICAL ABSTRACT



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ABSTRACT

Surrogates are used in conservation planning to select sites to represent species when information about species' geographical distributions is insufficient. Many surrogates for biodiversity have used biotic (e.g., vegetation assemblages) or biogeographic distributions of a group of species (e.g., birds) that are easier to inventory than more cryptic species of interest. Because knowledge of species geographical distributions is mostly limited, environmental diversity (ED), an approach that uses environmental dissimilarity between sites to select areas for conservation, is a promising alternative surrogacy strategy. While studies in the terrestrial realms justify further investigations of the effectiveness of ED as a surrogate to determine conservation priority of sites, ours represents a significant expansion of this focus to consider the marine realm. In this study, we defined environmental space using nine variables and evaluated ED as a surrogate of global marine mammal species. We found that ED is an effective surrogacy strategy for marine mammals: sites selected to span environmental diversity represented 61% more marine mammals, on average, than a random subset of sites. Although the effectiveness of ED has been demonstrated in previous studies of terrestrial vertebrates, we believe this is the first time ED is assessed as a surrogate in marine systems at the global scale. Our findings suggest that ED may also be useful to prioritize sites for conservation of other marine taxa.

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Introduction

Systematic conservation planning aims to prioritize areas for conservation action, such that the greatest biodiversity is represented while minimizing implementation costs (Rodrigues and Brooks, 2007; Moilanen et al., 2009). To select sites that efficiently represent species, conservation scientists and biogeographers rank sites by complementarity; that is, their ability to add species to the set of species already represented in a set of notionally conserved sites. Thus, sites are prioritized for conservation by preferentially selecting sites with higher numbers of unprotected species. The resulting set of sites represent many more species than if sites had been selected using species richness alone (Kirkpatrick, 1983; Csuti et al., 1997; Albuquerque and Beier, 2015a, b, and papers cited therein). If all sites have been inventoried for species of interest, highly complementary sites can be selected using integer programming (Haight and Snyder, 2009), or by using heuristic algorithms such as Zonation — a reserve-selection software (Moilanen et al., 2014).

Because of the limited knowledge about species and their distributions, conservation planners and biogeographers often use surrogates, such as terrestrial land cover types (Hunter, 1991), well-mapped taxa (Lewandowski et al., 2010), or environmental variables (Faith and Walker, 1996) to prioritize sites for conservation. Abiotic variables (e.g., temperature and topography) have been used to define surrogates for terrestrial (Faith and Walker, 1996; Beier and Albuquerque, 2015; Albuquerque and Beier, 2018) and marine (McArthur et al., 2020; Sutcliffe et al., 2015) biodiversity, and in each case, the surrogates identified sites with high complementarity.

One approach to using abiotic factors as a surrogate is environmental diversity (ED). ED organizes sites in continuous multidimensional environmental space that is assumed to be correlated to species assemblage space, and then uses a p-median algorithm to select sites that span the environmental space (Faith and Walker, 1996; Faith, 2003). The p-median approach starts by creating a uniform grid of hypothetical demand points across the ordination space, and then selects the subset of sites that minimize the distance (in raw multivariate space or ordination space) from each demand point to the nearest selected site (Faith and Walker, 1996; Faith, 2003; Hortal et al., 2009; Beier and Albuquerque, 2015). Another ED approach, Maxdisp (Engelbrecht et al., 2016), does not use demand points, but instead selects the sites with the highest sum of squares of distances among all pairs of selected sites. Engelbrecht et al. (2016) and Albuquerque and Beier (2018) concluded that Maxdisp was at least as effective as continuous p-median in selecting sites that efficiently represent species and has the advantage of faster and simpler computation.

Previous studies in the terrestrial realm have reported that ED is a highly effective surrogacy strategy of plants and vertebrates in tropical and temperate regions (Beier et al., 2015; Albuquerque and Beier, 2018). These findings justify further studies as to the effectiveness of ED as a surrogacy strategy to determine the conservation priority of sites. ED can be particularly meaningful in areas of the world where knowledge of species geographical distributions is most limited, such as tropical regions that might be experiencing rapid biodiversity loss (Pimm, 2000). The present study represents an important expansion of this focus to consider the marine realm. If effective, ED would be especially useful because most ocean areas have not been inventoried for marine mammals and other taxa (Schipper et al., 2008; Mora et al., 2011; Magera et al., 2013).

In marine systems, Sutcliffe et al. (2015) studied how well abiotic variables represented species belonging to a network of reserves in an Australian inter-reef system and found that abiotic information can help design marine reserves. If our hypothesis that ED is an effective surrogacy strategy for marine mammal representation is supported, it would suggest that ED could be used in marine systems as an alternative strategy whenever biological information is limited or lacking. Subsequent studies can then test if ED can also be an efficient surrogacy strategy for other marine taxa. Otherwise, negative results would suggest that although ED is an effective surrogacy strategy in the terrestrial context, it might not be equally applied to the marine landscape, at least in the case of marine mammals. In addition to testing the efficiency of ED as a surrogacy strategy for marine mammals, we also investigated whether the choice of oceanographic variables could affect its effectiveness (Albuquerque and Beier, 2018).

Materials and methods

Data preparation

We obtained range maps depicting the distribution of 123 marine mammals from the International Union for the Conservation of Nature (IUCN) Red List Spatial Data database (IUCN, 2021). We processed these range maps using the R package *letsR* (Vilela and Villalobos, 2015) to generate presence/absence values for each 1° grid cell of the world's oceans (N = 46,130). We excluded species that occur only in freshwater or are listed as Extinct by the IUCN. Species listed as Not Evaluated (NE) by the IUCN were also not part of our study because there are no range maps available for them.

We conducted separate analyses for 7 subsets or groups of the 123 marine mammals, plus an eighth group that included all species. Two subsets were related to use of land: Fully-aquatic (FA; n = 87 cetaceans and sirenians) or Non-fully aquatic (semi-aquatic) (NFA; n = 36 pinnipeds and fissipeds). Three groups related to migratory status: Migratory (MI; n = 37), Non-migratory (NMI; n = 52) or Unknown migratory status (UNK; n = 29). There were too few nomadic species (n = 5) for a separate analysis. Finally, we evaluated ED separately for threatened species (TR; n = 52) and species listed as Least Concern (Non-threatened species or NTR; n = 71). The TR group included species listed as Critically Endangered (CR; n = 3), Endangered (EN; n = 17), Vulnerable (VU; n = 13), Near Threatened (NT; n = 9), and Data Deficient (DD; n = 10). We included DD species in the TR group because Parsons (2016) argued that most DD cetaceans (all DD species are cetaceans) are likely to be threatened, and larger proportions of marine mammals than terrestrial mammals are threatened (Schipper et al., 2008). We also included NT as threatened because NT species are likely to become qualified as threatened in the near future (IUCN, 2012) (Table S1).

For each of the 46,130 1° marine cells or study sites, we considered nine environmental variables expected to affect species distributions at the global extent. Variables were obtained from the World Ocean Atlas (WOA, Boyer et al., 2018). The WOA is a collection of oceanographic variables aimed at depicting the ocean profile data (Garcia et al., 2019). Variables included objectively analyzed annual mean surface values for temperature, salinity, dissolved oxygen, percent oxygen saturation, apparent oxygen utilization, silicate, phosphate, and nitrate from the National Centers for Environmental Information (NOAA, Boyer et al., 2018). We also obtained gridded bathymetric (depth) values for each 1° cell from the Global Ocean and Land Terrain models (GEBCO 30 arc-second grid, GEBCO, 2014).

Measuring complementarity

Complementarity provides widely-used values that represent optimal solutions for species in the least number of sites (see e.g., Williams et al., 1996; Albuquerque and Beier, 2015a; Veach et al., 2017). We used the core-area function of the reserve-selection software Zonation (Moilanen et al., 2014) to produce a hierarchical ranking of conservation priorities based on complementarity of every 1° marine cell on Earth for each marine mammal group, based on their distribution maps. Zonation is deterministic and produces a complementarity-based ranking of conservation values over the entire landscape.

Measuring environmental diversity (ED)

We used the Maxdisp ED approach (Engelbrecht et al., 2016) and two sets of environmental variables for selecting environmentally diverse sites. The first set encompassed all oceanographic variables (ED_{all}). The second set included temperature, bathymetry and salinity (ED_{sel}); variables known to be related to conservation priority for marine mammals at a global extent (Astudillo-Scalia and Albuquerque, 2020). Maxdisp uses a Euclidean environmental distance matrix among the grid cells (sites) and the inverse of the square of distances between sites to calculate environmental dissimilarities between sites and to select sites maximally dispersed in the environmental space (Engelbrecht et al., 2016). After excluding the cells with missing environmental data, we used 40,401 cells in the analyses.

We used the Species Accumulation Index, SAI (Ferrier and Watson, 1997; Rodrigues and Brooks, 2007) to evaluate the ability of ED_{all} and ED_{sel} to identify sites that most efficiently represent species across 91 targets, ranging from 0.1 to 5.0% (by 0.05 increments) of the most environmentally diverse sites. SAI measures surrogacy values and compares the performance of the surrogate (ED_{all} and ED_{sel}) to the optimum/near optimum result (Zonation) and the randomly-selected sites result. SAI is expressed by: $(S-R)/(O-R)$, where S is the number of species represented in sites with the highest predicted complementarity ranks, O is the maximum number of species that can be represented in the same number of sites (based on complementarity values), and R is the number of species represented in the same number of randomly selected sites. SAI is scaled $-\infty$ to 1; negative SAI indicates a worse than random result, 0 indicates random performance, and positive SAI is a measure of surrogate efficiency. For example, SAI of 0.8 indicates that ED is 80% as effective as having full knowledge of where species occur in its ability to improve on random selection of sites.

Results

For all eight groups and all percentages of sites prioritized (targets), Zonation solutions represented many more species than the same number of randomly-selected sites (Figs. 1 and 2). In general, sites prioritized by the ED_{all} approach represented more species than occurred in randomly selected sites for most datasets (Fig. 1). Random solutions were relatively more efficient at lower targets (Fig. 1). On the other hand, ED_{sel} generally represented significantly fewer species than the Zonation and random solutions (Fig. 2).

The effectiveness of ED_{all} and ED_{sel} as surrogates for species representation varied across groups. On average across all marine mammal groups and targets, ED_{all} solutions were 61% as effective as Zonation solutions in improving on random selection of sites. ED_{all} represented significantly more species than randomly selected sites for groups Migratory and Non-threatened (mean SAI 0.75 and 0.72, respectively). The lowest efficiency in represented marine mammals was observed for Non-migratory and Non-fully aquatic marine mammals (mean SAI 0.47 and 0.53, respectively). For ED_{sel}, the effectiveness was much lower, except for Threatened species (Table 1). SAI values ranged from -6.0 (Non-migratory) to 0.68 (Threatened). Most SAI values for ED_{sel}, are negative, indicating a performance that is worse than random solutions (Table 1).

Table 1
Species accumulation indices (SAI) values of environmental diversity (ED) calculated from oceanographic variables. SAI values are represented by the mean across 91 spatial prioritization targets. The confidence level (95%) is also displayed. All variables include mean surface values for temperature, salinity, dissolved oxygen, percent oxygen saturation, apparent oxygen utilization, silicate, phosphate, nitrate, and bathymetry. Selected variables include mean surface values for temperature, bathymetry and salinity.

Marine Mammal Groups	Variables	
	All	Selected
All species (ALL)	0.560 (0.05)	−0.316 (0.09)
Fully aquatic (FA)	0.596 (0.05)	0.026 (0.09)
Non-fully aquatic (NFA)	0.525 (0.06)	−0.732 (0.11)
Threatened, NT & DD (TR)	0.559 (0.05)	0.682 (0.09)
Non-threatened (NTR)	0.719 (0.17)	−0.568 (0.10)
Migratory (MI)	0.746 (0.08)	0.002 (0.06)
Non-migratory (NMI)	0.467 (0.06)	−6.007 (0.83)
Unknown migratory status (UNK)	0.703 (0.07)	−0.248 (0.10)

Discussion

While the efficacy of ED has been tested in the terrestrial realm (Faith and Walker, 1996; Faith, 2003, 2011, Faith et al., 1996, 2004, Beier and Albuquerque, 2015; Engelbrecht et al., 2016; Albuquerque and Beier, 2018), this study provides a comprehensive assessment of the effectiveness of ED as a surrogate of marine mammal groups. Even though Species Accumulation Index (SAI) values differed among groups, our results suggest that ED is close to complementarity-based models for two of the datasets we tested (Non-threatened and Migratory; Table 1). Potentially, the reason for these observed differences in efficiency is that ED assumes that all species have a unimodal distribution in environmental space (Beier and Albuquerque, 2016), congruent with findings of studies in geographical space (e.g., Brown and Thatje, 2014). However, some marine mammal species deviate from this pattern in geographical space (e.g., migrating species such as humpback whales have a trimodal distribution, with seasonal presence in tropical/subtropical regions and the poles), which might be affecting the performance of the model. Further studies are required to better understand the cause of these patterns. The efficiency of ED depends on the set of environmental variables used to define environmental space (Table 1) and the fraction of the landscape prioritized (Fig. 1). Results of the two ED models in our study suggest that including variables that are related to primary productivity (even when they are not related to marine mammals themselves; e.g., oxygen-related variables, phosphate, and nitrate), has a significant impact on the effectiveness of the ED model. This is likely due to the relationship between marine mammal distribution and primary productivity. For example, Roman and McCarthy (2010) showed that marine mammal fecal plumes can increase primary productivity by contributing an important source of nitrogen close to the surface, and that regions with higher marine mammal densities tend to have higher levels of productivity.

We found that ED_{all} provides an abiotic surrogate that is on average 61% as effective as known distribution maps. In a recent meta-analysis, Beier et al. (2015) reviewed 622 evaluations of the effectiveness of abiotic surrogates in representing species in terrestrial ecosystems and reported that the use of abiotic surrogates represented plants and vegetation types relatively well. Beier and Albuquerque (2015) tested the efficiency of ED in eight terrestrial datasets and showed that ED was 42% as effective as having knowledge of species distributions. Sutcliffe et al. (2015) evaluated the use of abiotic domains to measure the efficacy of different marine reserve systems in representing species for conservation purposes and reported that abiotic domains performed substantially better than random solutions.

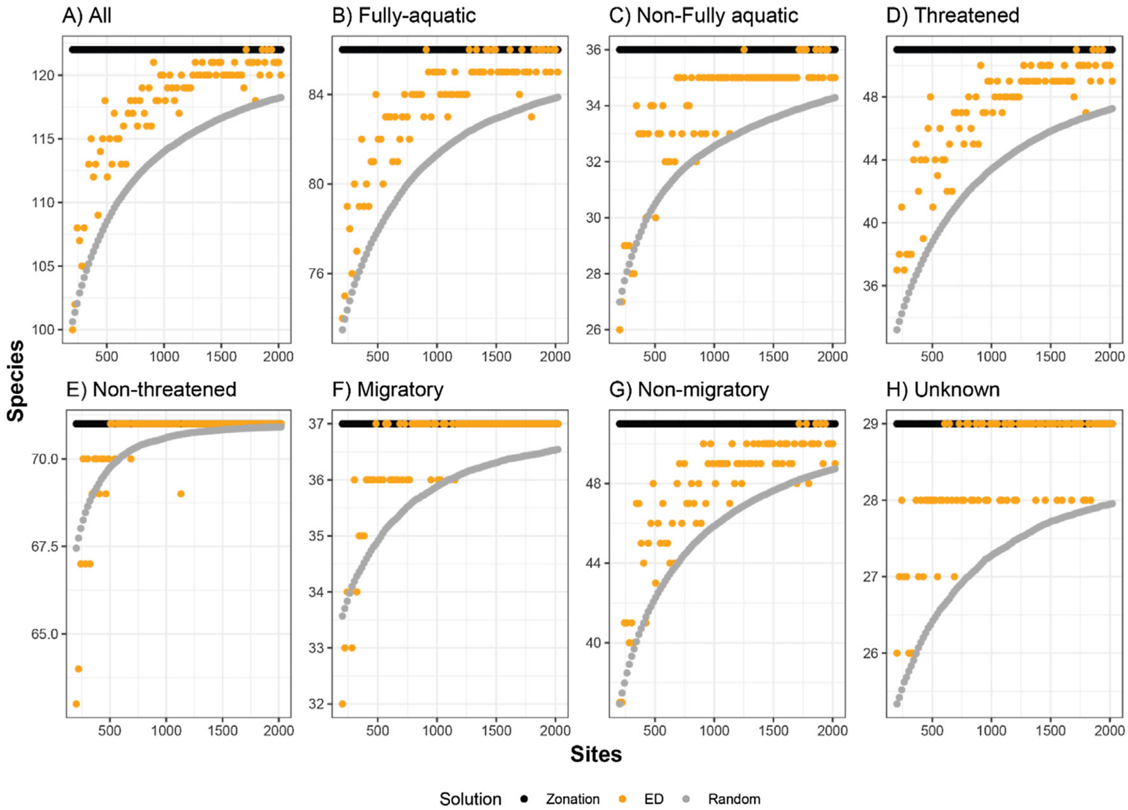

Fig. 1. Number of marine mammal species represented at least once in sites selected by environmental diversity (ED_{all}), and species represented at least once in sites selected by Zonation, compared to the number of species represented in an equal number of randomly selected sites. ED was calculated using all oceanographic variables. Curves are represented for eight marine mammal groups: (A) all species, (B) fully-aquatic, (C) non-fully aquatic, (D) threatened, (E) non-threatened, (F) migratory, (G) non-migratory, and (H) unknown migratory status.

As previously mentioned, the high efficiency of ED as a surrogate is linked to the variables used to define the environmental space and to the way ED selects sites for conservation. Abiotic data, and particularly ED, is an efficient surrogate of biotic representation because it selects sites to optimally span environmental space without the arbitrary constraints of binning methods, and because abiotic conditions are often associated with biogeographical patterns of plant and animal species richness, beta diversity, and patterns of sites complementarity (e.g., Currie, 1991; Hawkins et al., 2003; Field et al., 2005; Gaston et al., 2007; Albuquerque and Beier, 2015a). These studies suggest that energy and climate limit species richness over broad geographic extents (Hawkins et al., 2003 and references therein). An important assumption of using ED is that the values of oceanographic variables in a site reflect conditions experienced by marine species. Tittensor et al. (2010) investigated the global patterns and predictors of marine biodiversity and reported that temperature or kinetic energy plays a key role in structuring cross-taxon marine biodiversity. As indicated by the high efficiency of ED in identifying sites that represented species efficiently, our results show that variables related to diversity and complementarity can be used as abiotic surrogates to represent species in the marine realm. This follows the premise that areas with higher environmental diversity can host a greater diversity of species by providing a wider range of environmental conditions or niche space.

Additionally, our findings suggest that different species ought to be managed separately, and that each marine mammal group and environmental variables must be tested on a case-by-case scenario to determine the best abiotic surrogates to represent each species and/or groups. For example, results show that Non-threatened and Migratory species are the best represented by the ED model, while the worst groups represented by this model were Non-fully aquatic and Non-migratory (Table 1).

While we agree that results show that biotic informed solutions are still preferred if the distribution of species is well known, we also show that ED produces reliable solutions for marine mammals (Table 1). In an absence of knowledge about their geographical distribution (such as potential changes in their future distributions due to climate change; Silber et al., 2017), ED could provide the efficiency to meet conservation targets and help design alternative conservation areas, without having to wait for updated distribution maps. Considering that only a small fraction of biodiversity has been described or inventoried (Brown and Lomolino, 1998), and IUCN range maps should not be interpreted at spatial resolution finer than 1-degree cells (Hurlbert and Jetz, 2007), surrogacy strategies, such as ED, are needed for many taxa, especially at the fine spatial resolutions used for real world conservation planning. Since ED needs only abiotic data to select environmental diverse sites, and considering that abiotic data are widely available at finer and coarser resolutions, ED could represent an alternative to determine conservation priority of sites in places where the biographic distribution is lacking, and inventories are limited by budget constraints.

In conclusion, we found that ED could be an effective surrogacy strategy for marine mammals. This is the first study assessing the performance of ED as a surrogate of marine mammal biodiversity representation at the global scale. We propose that our results justify further studies on how ED can be used in applied conservation of marine species by complementing the available biotic information and thus increasing the overall tests of the effectiveness of the surrogates. This is in alignment with the findings by Rodrigues and Brooks (2007) and Sutcliffe et al. (2015), who reported that

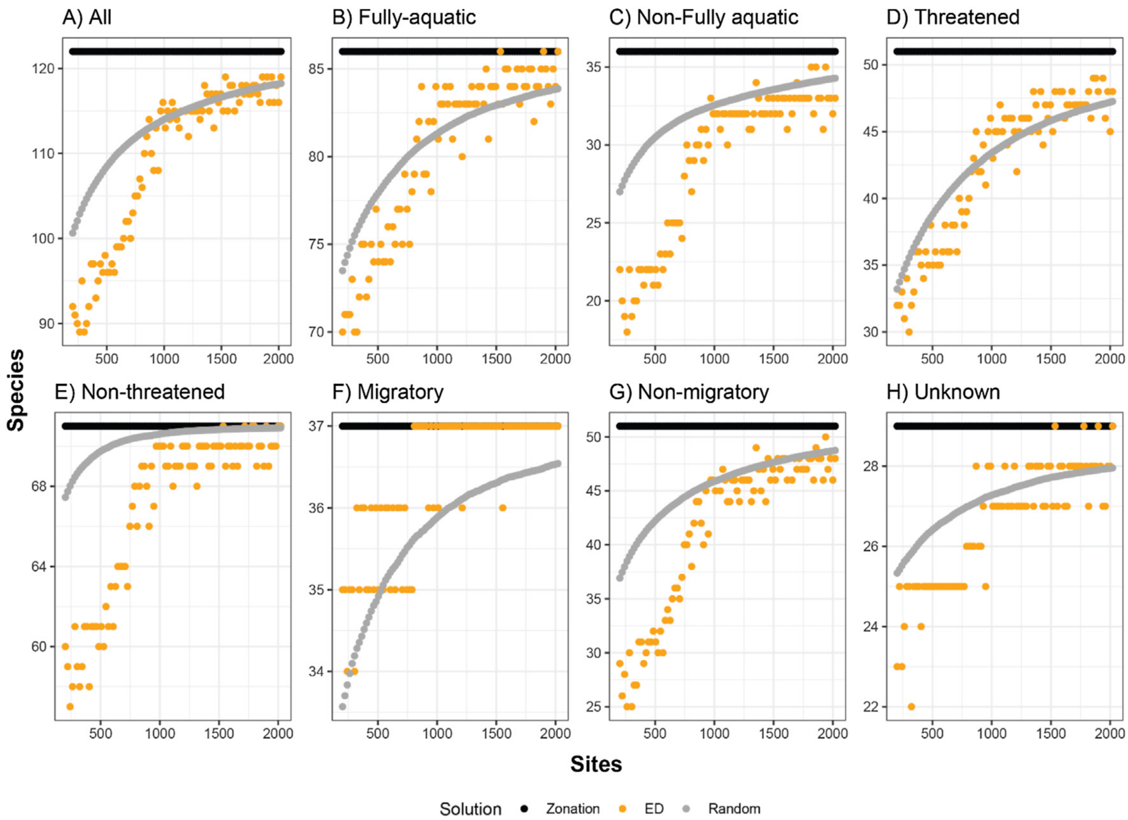

Fig. 2. Number of species represented at least once in sites selected by environmental diversity (ED_{sel}), and species represented at least once in sites selected by Zonation, compared to the number of species represented in an equal number of randomly selected sites. ED was calculated from selected variables (temperature, bathymetry and salinity). Curves are represented for eight marine mammal groups: (A) all species, (B) fully-aquatic, (C) non-fully aquatic, (D) threatened, (E) non-threatened, (F) migratory, (G) non-migratory, and (H) unknown migratory status.

biologically informed environmental surrogates, those that incorporated biological variables to develop their models, improved the efficiency of abiotic data as a surrogate of biodiversity.

Additionally, we must highlight that the results of our study are in a theoretical framework and therefore not yet ready to be applied in conservation of marine mammals. Range maps often overestimate the presence of species (Hurlbert and Jetz, 2007), and this overestimation may affect conclusions in the identification of efficacy of ED. To make our results more applicable to conservation action, biotic data comprising species-specific life history information such as population density estimates per site, minimum home range data, use of areas and seasonality (i.e., feeding areas versus breeding areas, especially in the case of migratory species), minimum coverage required for effective conservation outcomes (as representation by at least one cell in our model might not be adequate for some species), and other logistical information should all be determined and incorporated into our results. Nonetheless, because these factors are required in the implementation of a marine protected area even if site prioritization is calculated based on entirely biotic metrics such as species richness, we believe that our work as it stands already represents an improvement on site prioritization by complementing available biotic information even when it is scarce.

In the future, when biological information is available, biologically-informed multivariate procedures such as gradient forests (Ellis et al., 2012) and generalized dissimilarity models (Ferrier et al., 2007) can be used to identify the variables that affect most species distributions, therefore increasing the accuracy of ED as a surrogate. Additionally, increasing our knowledge of marine mammal species distributions would help increase the accuracy of abiotic surrogates. Unfortunately, this is challenging to do for marine mammals given the logistics and expenses associated with survey efforts, especially for pelagic species. This lack of detailed distribution data is also what justifies studies such as this one. Indeed, determining if ED is an effective surrogate of marine mammal biodiversity and thus appropriate to identify priority areas for conservation, can aid conservation actions when there is a lack of knowledge of species distributions (e.g., Data Deficient species, species that have not yet been evaluated, and those with unknown migration status), as well as when resources are limited, because abiotic data are easier and more affordable to obtain.

Declaration of Competing Interest

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

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.pecon.2021.08.002.

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PERSPECTIVE

PEOPLE AND NATURE BRITISH ECOLOGICAL SOCIETY

Co-management of culturally important species: A tool to promote biodiversity conservation and human well-being

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Abstract

1. Co-management has been advocated as an effective tool to achieve natural resource conservation worldwide. Yet, the potential of co-management arrangements can fail to be realized when there is insufficient local engagement.
2. In this perspective paper, we argue that co-management schemes focusing on culturally important species (CIS) can help overcome this issue by engaging local people's interest.
3. To develop this theory, we explore published data on the outcomes of two management schemes, both encompassing multiple independent initiatives, to discuss CIS-management effects and benefits.
4. We also show a compilation of CIS examples throughout the world and discuss the potential of CIS-management to reach a global audience.
5. Based on these data, we argue that CIS-management can be an effective tool to reconcile the often intractable goals of biodiversity conservation and human welfare.

KEYWORDS

Amazon, *Arapaima* spp., collaborative management, cultural keystone species, culturally significant species, *Podocnemis* spp, resource use, traditional people

1 | INTRODUCTION

Collaborative management (co-management) of natural resources has become increasingly widespread worldwide, especially after the 1980s, when local people, conservationists, and researchers began searching for alternatives to the often unsuccessful top-down management schemes prevalent at the time (Berkes, 2009; Jentoft, 1989; Pomeroy & Berkes, 1997). Co-management implies a participatory decision-making process in which the regulation of natural resource use is shared between the users and other stakeholders, such as the national or subnational government, NGOs and local cooperatives (Berkes, Mahon, & McConney, 2001). In cases where local people are exerting continuous direct influences on species and their habitats, such locally inclusive management approaches tend to be more effective and successful for natural resource conservation than non-participatory systems (Cinner et al., 2012; Gutiérrez, Hilborn, & Defeo, 2011; McClanahan, Marnane, Cinner, & Kiene, 2006).

Despite its widely acclaimed potential, co-management arrangements can also fail (Béné et al., 2009; Jentoft, McCay, & Wilson, 1998; Terborgh & Peres, 2017), often due to lack of local community involvement (Jentoft, 2000) or frail official institutional support (Terborgh & Peres, 2017). When official enforcement is absent or ineffective, local engagement may be the only way to ensure an effective vigilance system to enforce compliance by outsiders (Cinner et al., 2012). Poor enforcement is ubiquitous in developing countries, typically because of underfunding, understaffing, or low political priorities with conservation goals (Berkes et al., 2001; Campos-Silva, Fonseca Junior, & Silva Peres, 2015). Yet, tropical developing countries host most global biodiversity hotspots (Myers, Mittermeier, Mittermeier, da Fonseca, & Kent, 2000), and most of the world's rural poor, who depend directly on natural resources for subsistence and to support local economies (Fisher & Christopher, 2007). Therefore, natural resource conservation based on local engagement is both ecologically appealing, and critical to maintain food security and social stability in developing countries (Adams, 2004; Adenle, Stevens, & Bridgewater, 2015).

Achieving local engagement in a co-management scheme can be challenging, as several factors may influence local interest and commitment (see e.g. Mistry et al., 2016; Ruiz-Mallén, Schunko, Corbera, Rös, & Reyes-García, 2015; Seixas & Davy, 2008). Yet, successful cases of self-organization are normally associated with users being strongly attached to the resources in focus, which either support a substantial portion of local livelihoods or have a high value assigned to its sustainability (Measham & Lumbasi, 2013; Ostrom, 2009). Otherwise, the costs of local engagement may not be worth the effort (Ostrom, 2009). In this paper, we argue that placing culturally important species as the focus of management schemes is a powerful mechanism to engage local communities with conservation initiatives.

Culturally important species are those highly significant for local people, with prominent functional roles in their diet, materials, medicine, cultural identity and/or spiritual values (Cristancho & Vining, 2004; Garibaldi & Turner, 2004). The concept of 'cultural keystone species' (CKS) was proposed to refer to these species as an analogy to the ecological concept of 'keystone species' (sensu Paine, 1969; Power et al., 1996). As such, CKS corresponds to species crucial to the survival of a people's culture, without which the society they support would be completely different (Cristancho & Vining, 2004; Garibaldi & Turner, 2004). Here we use the more comprehensive term 'culturally important species' (CIS) considering that some species may play an overriding role in people's culture yet are not necessarily irreplaceable and indispensable to the culture's survival. Nevertheless, the local extinction or decline of CIS will always be critical to local peoples, likely affecting not only their subsistence and/or spirituality, but also the transmission of Traditional Ecological Knowledge (TEK; Berkes, 2008) and the continuity of traditional practices related to the species.

Considering the huge impact CIS may have on local peoples' lives, it has been argued that these species should be taken into account by management and conservation monitoring approaches in order to ensure local people's long-term access to them (Cristancho & Vining, 2004; Noble et al., 2016). Furthermore, local people should have the inherent right to participate in the decision-making in managing these species, which have played fundamental socio-cultural roles for generations (Butler, Tawake, Skewes, Tawake, & McGrath, 2012; Garibaldi, 2009; Noble et al., 2016). Beyond the relevant issues of social justice, studies have also highlighted the potentially positive ecological consequences of CIS-management (Cristancho & Vining, 2004; Garibaldi, 2009; Garibaldi & Turner, 2004; Noble et al., 2016). These authors built their assumptions on multiple arguments, based mainly on the following ideas: (a) if local people identify strongly with a certain species, they will have a strong desire to preserve or restore such species, which favours conservation success (Garibaldi, 2009; Garibaldi & Turner, 2004); (b) focusing on CIS is a way to simultaneously address ecological and cultural concerns, and having a focal set of species may be financially and logistically more manageable (Garibaldi, 2009; Garibaldi & Turner, 2004); (c) the decline of a CIS may negatively affect local stakeholders who are effectively caring for local natural resources, which may consequently affect the stability of the ecosystem (Cristancho & Vining, 2004); (d) CIS are often vital species to the ecosystem where they occur, thereby their conservation should be beneficial for both local people and the environment (Noble et al., 2016); and (e) the population recovery of CIS and their habitats will support the reclamation of the habitat for associated species (Garibaldi, 2009).

Despite expectations about the positive outcomes potentially generated by CIS-management, studies that actually show real-world results are scarce. Moreover, the use of quantitative data to support the beneficial outcomes of using CIS-management approaches is highly limited. This limitation is problematic as policy-makers and managers often need quantitative data to support their decisions, particularly those related to species' management. Here we attempt to fill this knowledge gap by compiling quantitative data on the ecological, social, and economic outcomes of two co-management schemes focused on CIS, with the support of multiple independent initiatives. The data is literature-based, derived mostly from ecological studies. Even though both schemes are focused on CIS, these studies normally fail to address the impact of the species' cultural importance to the success of the initiatives. Success is generally attributed to the engagement of local people, but the triggers promoting such successful engagement are rarely mentioned.

By assembling arguments from CIS studies and results from the two case studies, we discuss how focusing on CIS in management schemes is a way to motivate local people interest and involvement. A consequence of local engagement will be positive conservation outcomes, even in cases where institutional resource governance is severely limited, as in most developing countries. Finally, we provide a compilation of CIS examples from around the world to discuss the potential of CIS-management to be established across a wide range of geographic contexts.

2 | MATERIALS AND METHODS

We analysed two prominent co-management schemes established in the freshwater ecosystems of the Brazilian Amazon. The Amazon is responsible for Brazil being one of the five countries that together contain more than 70% of the world's wilderness (Watson et al., 2018). At the same time, thousands of rural communities live in the

Amazon and rely directly on natural resources for their survival. Such a scenario makes it imperative to develop strategies seeking to reconcile biodiversity conservation with the maintenance of local people's culture and livelihoods. We chose two examples of currently CIS management strategies, which have several independent initiatives spread over a large geographic scale (Figure 1). The first one refers to the arapaima (*Arapaima* spp.; Figure 2) fisheries management, and the second to the conservation of freshwater turtles (*Podocnemis* spp.; Figure 3) through the protection of fluvial sand beaches. We explore both schemes to discuss their main outcomes and limitations. The data used comes from the literature and from personal direct observations in the field by the authors.

In addition to the two case studies, we present a compilation of CIS examples from other parts of the world in order to illustrate the wide range of species that are highly relevant to local societies worldwide. Providing a full compilation of CIS examples from all

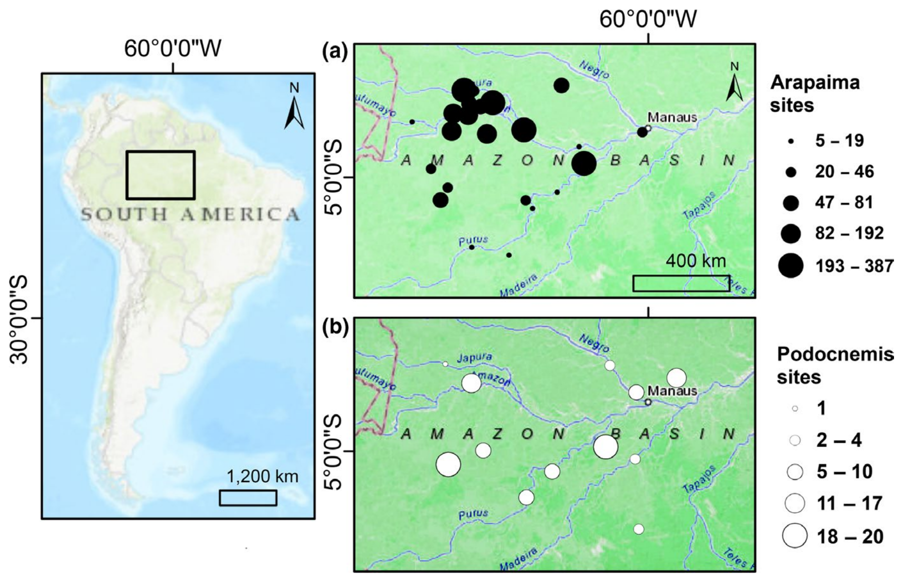


FIGURE 1 Geographic distribution of co-management schemes for two culturally important genus (*Arapaima* spp. and *Podocnemis* spp.) within the State of Amazonas, in the Brazilian Amazon. Left: map of South America indicating the large geographic region (black rectangle) where both co-management schemes are currently established. Right: distribution of (a) *Arapaima* spp. (black circles) and (b) *Podocnemis* spp. (white circles) co-management schemes within the black rectangle. Circle sizes are proportional to the number of co-management areas (water bodies/beaches) within each location. Data on the location of arapaima co-management water bodies were obtained from the Brazilian Environmental Agency (IBAMA), while the location of protected beaches focusing on *Podocnemis* spp. conservation was obtained from a governmental official bulletin (Amazonas Official Diary, N° 33604, 14th September 2017)

FIGURE 2 Photos of *Arapaima* spp. (a) An arapaima individual in an aquarium (Photo: Pedro Peloso); (b) Fishermen hauling arapaima into the boat during nocturnal fishing in the Juruá River basin (Photo: Carolina Freitas); (c) Fisherman weighing an arapaima individual in the Purus River basin (Photo: Carolina Freitas). Note: According to ethical standards, all persons shown here authorized the use of their photographs

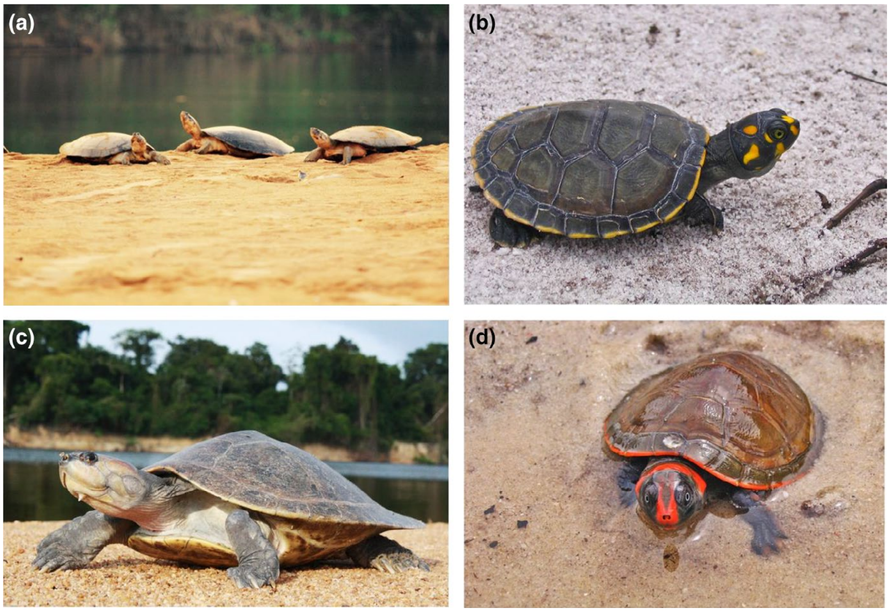


FIGURE 3 Photos of *Podocnemis* spp. (a) *P. expansa* (Photo: Camila Ferrara); (b) *P. unifilis* (Photo: Camila Ferrara); (c) *P. sextuberculata* (Photo: Fernanda Rodrigues); and (d) *P. erythrocephala* (Photo: Camila Ferrara)

over the globe is beyond the scope of this paper. Instead, we present a limited list of examples based on an online search in the Web of Science database using the search terms '*cultural keystone species*' *OR* '*culturally important species*' *OR* '*culturally significant species*' *OR* '*tabooed species*' *OR* '*cultural taboo*' (all in English). We also used snowballing techniques, by including citations found within the search publications. Our compilation was restricted to animal species only. The examples were gathered in a table with information on (a) the common and scientific names of the species, (b) its general taxonomic group, (c) its geographic location, (d) the culture that has identified the species as a CIS, (e) the species' local uses and values, and (f) the references citing each example. The information used to fill the table came from studies found in our search and consequently do not necessarily correspond to all data available to each species in other possible sources.

3 | CASE STUDIES

3.1 | Arapaima co-management

Arapaima is one of the largest freshwater fish on Earth, and an iconic element of the Amazon (locally known as *pirarucu* in Portuguese, or *paiche* in Spanish; Figure 2). *Arapaima* spp. inhabit lakes and water channels during the dry season and migrate laterally to flooded forests when the water levels rise (Castello, 2008). The individuals are mainly fished during the dry season, when they are concentrated in the discrete water bodies. Arapaima plays a central role in the livelihood and cultural identity of many Amazonian peoples since pre-Columbian times, being an important source of animal protein (Bates, 1863; Prestes-Carneiro, Béarez, Bailon, Rapp Py-Daniel, & Neves, 2016; Veríssimo, 1895), local medicine (Alves & Rosa, 2007), and a key element in sociocultural practices and local cosmologies (Aparicio, 2014; Murrieta, 1998, 2001).

During the 19th and early 20th century, arapaima was the most important commercial fishery resource in the Brazilian Amazon (Mérona, 1993; Veríssimo, 1895), which led to its overfishing in many areas (Castello, Arantes, Mcgrath, Stewart, & Sousa, 2014). The expansion of commercial fisheries across the Amazon River and its major tributaries from the 1960s onwards, driven by increased fishing technologies, further aggravated the situation of arapaima stocks, as well as other species (McGrath, de Castro, Futemma, de Amaral, & Calabria, 1993). Facing such excessive fishing pressure and its negative consequences, some riverine communities started grassroots movements seeking to take control of local water bodies and implement local agreements to regulate fishing activities (De Castro, 2002; De Castro & McGrath, 2003; McGrath, Cardoso, Almeida, & Pezzuti, 2008; McGrath et al., 1993). These so-called *fishing agreements*, starting in the 1980s, came to be legally accepted by the Brazilian government in the late 1990s, representing an innovative formal instrument of collaborative fisheries management (De Castro & McGrath, 2003; McGrath et al., 2008). This process created the basis for the subsequent establishment of other fisheries co-management models in the Amazon, such as the arapaima co-management.

Arapaima co-management started as an alternative to reconcile the recovery of arapaima stocks with its sustainable harvest, since arapaima fisheries had been banned by local legislation in the 1990s but illegal fishing continued in the absence of adequate enforcement (Castello & Stewart, 2010; Cavole, Arantes, & Castello, 2015). The first arapaima co-management initiative was undertaken in the early 2000s, in the Mamirauá Sustainable Development Reserve (Solimões River basin), and showed promising results (Castello, Viana, Watkins, Pinedo-Vasquez, & Luzadis, 2009). After the proven success of this experience, the scheme was accepted by the Brazilian Environmental Agency (IBAMA) as a model to be replicated in other areas, which opened the possibility of legal arapaima fishing under specific conditions (Amazonas Normative Instruction N°1, 1st June

2005). The model is based on a quota system set according to the arapaima abundance within the management areas (Castello et al., 2009). The abundance is annually estimated by local people through direct visual counts; this is possible because arapaima is an obligate air-breather coming to surface every ~15 min, which enables fishers to count the number of individuals in the lakes and water channels based on TEK and following a standardized protocol (Castello, 2004). IBAMA is in charge of setting the next-year quota for each community, which is allocated as a one-off annual harvest, normally lasting from a few days to one month. In order to award IBAMA's approval to start an arapaima co-management system, the community must design a management plan, which includes the zoning of the water bodies (including no-take lakes) and the establishment of a local vigilance system to preclude illegal fishing (Castello et al., 2009; Amazonas Decree N° 36083, 23rd July 2015).

Arapaima co-management plans have proliferated throughout the Amazon over the last years, currently encompassing >3,000 fishing households from >450 rural communities (IBAMA, personal communication). Studies have highlighted the positive ecological and socioeconomic impacts of the activity. For instance, the number of arapaima adults increased up to 24-fold after 8 years of arapaima co-management in the Solimões River basin (Castello et al., 2009); up to 29-fold after six years of co-management in the Purus River basin (Petersen, Brum, & Rossoni, 2016); and up to 30-fold after 11 years of co-management in the Juruá River basin (Campos-Silva & Peres, 2016). In all cases, arapaima declined or remained stable at low densities in neighbouring water bodies not included in the co-management scheme (Campos-Silva & Peres, 2016; Castello et al., 2009; Petersen et al., 2016). Models testing the effect of several environmental and social predictors on the arapaima abundance, showed that the presence of the co-management scheme was the strongest one, accounting for over 70% of the observed variation in arapaima numbers (Campos-Silva & Peres, 2016). Importantly, other aquatic species also benefit from increased abundance with the protection of the water bodies, such as the high-value *tambaqui* fish (*Colossoma macropomum*; Arantes & Freitas, 2016; Silvano, Ramires, & Zuanon, 2009), freshwater turtles (*Podocnemis* spp.; Miorando, Rebêlo, Pignati, & Brito Pezzuti, 2013), and caimans (*Melanosuchus niger*; Projeto Médio Jurua, unpublished data).

Arapaima co-management also brings socio-economic benefits to the rural communities. All arapaima harvested are sold by the local people through a simplified value chain, which results in a significant extra income. After 10 years of arapaima management in the Solimões River basin, the per capita income from arapaima sales increased five-fold (Amaral, 2009). In the Juruá basin, co-managed lakes ensure an average annual revenue of nearly US$ 10,600 per community and US$ 1,050 per household (Campos-Silva & Peres, 2016), which corresponds to about four times the Brazilian minimum wage. Such extra income is highly relevant to local people, who have a largely subsistence lifestyle with limited cash-earning opportunities, often earning less than the minimum wage per month. Furthermore, revenues from arapaima sales are received as an annual windfall, which enables investments that local participants could not make otherwise, including improvements in fisheries enforcement and in communal assets, such as local schools, medical care, and power generators for household and community lighting (CTF and JVCS, personal observation). In addition to the economic outcomes and its indirect social benefits, interviews with self-declared former illegal arapaima fishers showed that most of them (75%) highlighted that arapaima co-management helps strengthen cultural values, and many (68%) declared that local people's pride and self-esteem increased due to the success they achieved in restoring arapaima populations (Campos-Silva & Peres, 2016). Some interviewees (28%) also mentioned the more equitable income distribution as another important outcome, since arapaima fisheries are now a collective enterprise rather than having the benefits concentrated in only a few experienced fishermen (Campos-Silva & Peres, 2016).

3.2 | Freshwater turtle conservation through fluvial sand beach protection

The genus *Podocnemis* includes four extant species of freshwater turtles in the Brazilian Amazon, all of them commonly used by local people: The giant South American turtle (females locally known as *tartaruga* and males as *capitarí*; *Podocnemis expansa*; Figure 3a), the yellow-spotted river turtle (*tracajá*/*zé prego*; *P. unifilis*; Figure 3b), the six-tubercled river turtle (*iaçá*/*pitiú*; *P. sextuberculata*; Figure 3c), and the red-headed river turtle (*irapuca*; *P. erythrocephala*; Figure 3d). These four species occur in rivers, lakes and floodplain forests, and use fluvial beaches to nest (IUCN, 2018; Smith, 1979).

Podocnemis spp. play a central role in the livelihood and cultural identity of many Amazonian peoples since pre-Columbian times (Bates, 1863; Carvajal, 1894; Prestes-Carneiro et al., 2016; Silva-Coutinho, 1868; Veríssimo, 1895). Local people value both adults and eggs for multiple purposes, especially as food delicacy and medicinal resource, in addition to being a highly important item in social practices and celebrations (Alho, 1985; Alves & Rosa, 2007; Alves et al., 2012; Johns, 1987; Pezzuti, Lima, Silva, & Begossi, 2010; Rebêlo & Pezzuti, 2000; Smith, 1974). *Podocnemis* spp. are also greatly valued by riverine peoples as a special food item to diversify their otherwise monotonous fish-based diet (Murrieta, 1998).

During the 18th and 19th centuries, following the European colonization, millions of freshwater turtles were slaughtered yearly, and their eggs widely converted into oil for cooking and urban lightning (Smith, 1979). This scenario led to a sharp decline in turtle populations. In the 1960s, a national law was established in Brazil banning the hunting and commercialization of wild animals (Brazilian Fauna Protection Law, N° 5,197, & 3rd January, 1967), which consequently discontinued legal trade of turtles. However, high levels of illegal harvesting continued in the absence of adequate enforcement (Fachín-Terán, Vogt, & Thorbjarnarson, 2004; Kemenes & Pezzuti, 2007; Peñaloza, Hernández, & Espín, 2013). The situation was aggravated by the construction of highways and large hydroelectric dams directly impacting the nesting beaches (Alho, 2011; Norris, Michalski, & Gibbs, 2018a; Smith, 1979). Faced with the depletion of *Podocnemis* spp. stocks, local communities started on-the-ground conservation initiatives, focused on protecting turtle nesting beaches (Andrade, 2007). These initiatives were eventually supported by government institutions, NGOs and/or researchers, and proliferated throughout the Amazon (Andrade, 2007; Cantarelli, Malvasio, & Verdade, 2014).

The management scheme is based on the establishment of protected beaches whereby local beach guards are in charge of surveillance, and nest monitoring (IBAMA, 2016). Each protected beach is constantly surveyed, day and night, by one to three guards, to avoid poaching of adults and eggs during all the nesting period (dry season; ~5 months per year). In some places beach guards work on a voluntary basis, while in others they are financially supported by the local government and receive a monthly payment during the nesting period. The payment is delivered either in cash (amount equivalent to the Brazilian minimum wage, ~US$ 250/month) or, more commonly, as a food hamper (equivalent to less than half a minimum wage; ~US$ 110/month; Campos-Silva, Hawes, Andrade, & Peres, 2018).

Studies have highlighted positive impacts of turtle management schemes. For instance, comparisons between areas with and without the scheme, showed that in the Lower Amazon the managed areas had ten-fold more *P. sextuberculata*, and accounted for 91% of the total individuals caught in the entire study area (Miorando et al., 2013). In the Juruá basin, managed areas had 58 times more *P. expansa*, six times more *P. unifilis*, and three times more *P. sextuberculata* (Campos-Silva et al., 2018); moreover, 99% of all *P. expansa* nests recorded on unprotected beaches were raided by poachers compared to only 2.1% on adjacent protected beaches (Campos-Silva et al., 2018). Studies tested the effect of several environmental and social variables on turtle abundance, and community-based beach protection was the strongest one for both *P. sextuberculata* (Miorando et al., 2013) and *P. expansa* (Campos-Silva et al., 2018). Data accumulated through the *Podocnemis expansa* Conservation Program across nine states of the Brazilian Amazon showed that protected beaches produced at least 46 million hatchlings in 30 years, and resulted in *P. expansa* population recovery in most areas (Cantarelli et al., 2014). Furthermore, a study focusing on *P. unifilis* showed that two years of government enforcement patrols had no effect on nest illegal harvesting, whereas one year of co-management in the same area resulted in almost three-fold reduction of harvest levels (Norris, Michalski, & Gibbs, 2018b). In addition to *Podocnemis* spp., protected beaches benefit species from several other groups, such as beach-nesting birds, large catfishes, terrestrial invertebrates, river dolphins, caimans and green iguanas (Campos-Silva et al., 2018). The magnitude of differences in the abundance varies across species, with some being overwhelmingly more abundant on protected beaches (e.g. 83-fold for black skimmers, *Rynchops niger*; Campos-Silva et al., 2018).

In contrast to the arapaima co-management, the turtle management scheme does not represent a cash-earning opportunity for the community and cannot become financially self-sufficient over time, due to the legal impediment to the harvest and trade of turtles and their eggs in Brazil (Brazilian Fauna Protection Law, N° 5197, 3rd January 1967; Brazilian Environmental Crimes Law, N° 9605, 12th February 1998). The material benefits, if any, are restricted to the beach guards' nominal payment only, and are negligible considering the high workload the activity demands and the risks involved (Campos-Silva et al., 2018; Pezzuti et al., 2018). Indeed, beach guards are exposed to frequent threats of violence from poachers, including death threats (CTF and JVCS personal observation). The absence of tangible financial return is frequently mentioned by beach guards as one of the main concerns for the long-term sustainability of the activity (Campos-Silva et al., 2018). They also complain about the lack of appreciation of their role by government authorities and the wider society, who fail to adequately recognize the considerable time and effort they invest in the conservation scheme, and the personal risks they incur from confronting recalcitrant poachers (Campos-Silva et al., 2018). Another often expressed concern is the insufficient support from government agencies, both in terms of financial assistance—e.g. investment on basic equipment or on fuel for patrols—and official enforcement—e.g. application of formal sanctions to identified poachers (Campos-Silva et al., 2018; Pezzuti et al., 2018; CTF and JVCS personal observation). At the same time, however, beach guards often highlight the strengthening of local cultural values as a great positive outcome from the turtle conservation scheme (Campos-Silva et al., 2018). Furthermore, communities where protected beaches emerge are seen as privileged areas, and residents feel proud of the increasingly abundant turtle population (Pezzuti et al., 2018).

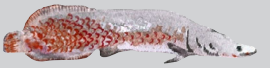
4 | CIS THROUGHOUT THE WORLD

The initiatives focusing on *Arapaima* spp. and *Podocnemis* spp. show important similarities and differences (Table 1) that have direct implications to their ecological, social, and economic outcomes (see Section 5). Despite particular bottlenecks, both case studies can be considered successful examples of CIS-management. Inspired on those experiences, other initiatives of CIS-management could be reproduced across multiple contexts. Each culture has its own CIS and often these have a strong effect on the ecosystem they inhabit, which make them especially relevant to management and conservation purposes (Close, Fitzpatrick, & Li, 2002; Noble et al., 2016). To illustrate the potential of CIS-management to span a wide geographic scale, we show a compilation of CIS examples in Table 2. Although this list is nowise exhaustive, it gives a sense of the comprehensive range of CIS existing worldwide, encompassing several taxonomic groups and environments, as well as different uses and values for various peoples.

5 | DISCUSSION

Even though the initiatives focusing on *Arapaima* spp. and *Podocnemis* spp. are naturally restricted to the Amazon, they bring relevant insights into wildlife management and conservation, applicable to multiple contexts throughout the world. Hereafter, we discuss some of the key learnings from our study and propose a general framework regarding CIS-management schemes.

TABLE 1 Similarities and differences between *Arapaima* spp. fisheries co-management, and *Podocnemis* spp. conservation through the protection of fluvial beaches

	***Arapaima* spp. co-management** 	***Podocnemis* spp. co-management** 
Target species		
Cultural importance	High	High
Historical commercial overpressure	High	High
Current illegal harvest pressure	High	High
Co-management features		
Rules focusing on habitat protection	Yes	Yes
Surveillance/enforcement	Local	Local
Participants' engagement	High	High
Community involvement	Strong	Moderate[a]
Main stimuli to local engagement	Economic and cultural	Cultural and moral/ethic
Personal risk to participants	High	High
Societal recognition and outreach	High	Low
Possibility of financial self-sustainability	Yes	No
Legal permission to trade the target species	Yes[b]	No
Benefits from the management scheme		
Increased abundance of the target species	Yes	Yes
Increased abundance of non-target species	Yes	Yes
Ecological benefits for the ecosystem	Yes	Yes
Contribution to food security	Yes	Yes
Strengthening of cultural values	Yes	Yes
Strengthening of local pride and self-esteem	Yes	Yes
Income generation	Yes	No[c]
Income distribution within the community	Yes	No

Note: Illustrations: Karla Koehler.

[a]Community involvement on turtle co-management (beach protection) varies across different locations. In many cases, however, only one to three beach guards are in charge of the management rather than the whole community.

[b]Trade of wild arapaima is allowed only under co-management schemes approved by the Brazilian Environmental Agency (IBAMA), who is in charge of setting annual quotas to each management unit according to the local arapaima abundance.

[c]In some locations beach guards receive a monthly payment during the turtle nesting period. This payment may be delivered either in cash or as a food hamper, and needs to come from external sources (e.g. local government or NGOs). The activity itself does not generate income due to Brazilian legal restrictions.

TABLE 2 Examples of Culturally Important Species (CIS) throughout the world[a]

CIS general group	CIS common and scientific names	People[b]	Country/Nation[b]	Local values and uses mentioned[b,c] (listed in alphabetical order)	References[b]
Bird	Cassowary (*Casuarius casuarius johnsonii*)	Djiru (Mission Beach)	Australia	Food, identity	Hill et al. (2010)
		Karam (Kaironk Valley)	Papua New Guinea	Oral tradition, symbolic value	Bulmer (1967)
	Glaucous-winged gull (*Larus glaucescens*)	Huna Tlingit (Southeastern Alaska)	USA	Food (eggs), identity, social practices, spirituality	Hunn, Johnson, Russell, and Thornton (2003)
	Kereru [New Zealand pigeon] (*Hemiphaga novaeseelandiae*)	Tuawhenua	New Zealand	Celebrations, food, spirituality, symbolic value	Timoti, Lyver, Matamua, Jones, and Tahi (2017)
	Muttonbird [Sooty shearwaters] (*Puffinus griseus*)	Rakiura	New Zealand	Celebrations, ceremonies, food, economy, social practices, spirituality, symbolic value	Mccarthy et al. (2014); Moller, Kitson, and Downs (2009); Moller, O'Blyver, et al. (2009)
	Ostrich (*Struthio camelus*)	Ikoma [some Abhaghetigha clans] (Serengeti District)	Tanzania	Sacred species, symbolic value	Kideghesho (2008)
	Vulture (*Gyps* spp.)	Parsee	India	Legends, practical utility (cleaning the environments and disposing human bodies), symbolic value	Markandya et al. (2008)
	White Stork (*Ciconia ciconia*)	Polish rural people	Poland	Beliefs, folklore, pest regulator in agriculture, symbolic value	Kronenberg, Andersson, and Tryjanowski (2017)
Crustacean	Crayfish (*Jasus edwardsii*)	Kaikōura	New Zealand	Food, identity, symbolic value	Mccarthy et al. (2014)
	Crayfish [Freshwater crayfish] (*Astacoides* spp.)	Betsileo and Tanala (Fianarantsoa Province)	Madagascar	Economy, food, social practices	Jones, Andriahajaina, Ranambinintsoa, Hockley, & Ravoahangimalala, (2006)
	Crayfish [Freshwater crayfish] (*Cambarus* spp. and *Astacus* spp.)	Cherokee, Chitimachas, Houmas, Choctaw, Attakapas	USA	Food, legends	Irwin (2014); Noble et al. (2016)
	Crayfish [Freshwater crayfish] (*Paranephrops planifrons* and *P. zealandicus*)	Māori	New Zealand	Food	Kusabs and Quin (2009); Noble et al. (2016)
	Crayfish [Murray crayfish] (*Euastacus armatus*)	Aboriginal peoples of the Murray-Darling River basin	Australia	Food	Humphries (2007); Noble et al. (2016)
	Marron (*Cherax tenuimanus* and *C. cainii*)	Aboriginal peoples of the Murray-Darling River basin	Australia	Food	Noble et al. (2016)
	Yabby (*Cherax destructor*)	Aboriginal peoples of the Murray-Darling River basin	Australia	Food	Humphries (2007); Noble et al. (2016)

(Continues)

TABLE 2 (Continued)

CIS general group	CIS common and scientific names	People[b]	Country/Nation[b]	Local values and uses mentioned[b,c] (listed in alphabetical order)	References[b]
Fish	Eel [American eel] (*Anguilla rostrata*)	Mi'kmaq	Canada	Ceremonies, food, legends, medicine, social practices, spirituality, symbolic value	Davis, Prosper, Wagner, and Paulette (2004); Mainland Nova Scotia Mi'kmaq (2011); Prosper and Paulette (2002); SRSF (2002)
	Eel [New Zealand freshwater eel] (*Anguilla dieffenbachia*, *A. australis* and *A. reinhardtii*)	Māori	New Zealand	Food, legends	McDowall (2011); Noble et al. (2016)
	Eel [Short-finned eel] (*Anguilla australis*)	Māori	New Zealand	Food, legends	Dolamore, Puddick, and Wood (2016); Mccarthy et al. (2014)
		Aboriginal peoples of South-west Victoria	Australia	Ceremonies, economy, food, social practices, symbolic value	Framlingham Aboriginal Trust and Winda Mara Aboriginal Corporation (2004); Noble et al. (2016)
	Herring [Pacific herring] (*Clupea pallasii*)	Heiltsuk (British Columbia)	Canada	Ceremonies, economy, food, social practices	Gauvreau (2015)
		Haida (Queen Charlotte Islands, British Columbia)	Canada	Bait for fishery, food, economy, oil source	Jones (2007)
		Alaska natives	USA	Celebrations, food	Moss (2015)
	Kahawai [Australian salmon] (*Arripis trutta*)	Te Whānau-a-Hikarukutai/ Ngāti Horomoana people	New Zealand	Celebrations, ceremonies, food, identity, narratives, social practices, spirituality, symbolic value	Maxwell, Horomoana, Arnold, and Dunn (2018)
	Lamprey [Pacific lamprey] (*Lampetra tridentata* and *Entosphenus tridentatus*)	Indigenous people of the Columbia River Plateau (e.g. Nez Perce, Umatilla, Warm Springs and Yakama)	USA	Ceremonies, celebrations, food, medicine, spirituality	Close et al. (2002); CRITFC (2011)
	Murray cod (*Maccullochella peelii*)	Aboriginal peoples of the Murray Darling River basin	Australia	Cosmology, economy, food, identity, symbolic value	Ginns (2012); Noble et al. (2016)
	Salmon [Atlantic salmon] (*Salmo salar*)	Mi'kmaq (Nova Scotia)	Canada	Celebrations, ceremonies, food, social practices, spirituality	Denny and Fanning (2016)
	Salmon [Pacific salmon] (*Oncorhynchus* spp.)	Gitga'at and other coastal peoples of British Columbia	Canada	Economy, food, identity	Garibaldi and Turner (2004); Healey (2009)
		Aboriginal peoples from Alaska, Canada, and the Pacific Northwest (300+ tribes)	USA Canada	Celebrations, ceremonies, food, economy, identity, spirituality	Bruce Johnsen (2009); Cozzetto et al. (2013); Dittmer (2013); Galbreath, Bisbee, Dompier, Kamphaus, and Newsome (2014); Garibaldi (2009); Haggan et al. (2004); Landeen and Pinkham (1999)

(Continues)

TABLE 2 (Continued)

CIS general group	CIS common and scientific names	People[b]	Country/Nation[b]	Local values and uses mentioned[b,c] (listed in alphabetical order)	References[b]
Mammal	Beaver (*Castor canadensis*)	Dene, Cree, and Métis (Fort McCay, Alberta)	Canada	Ecosystem function, technology	Garibaldi (2009)
	Boar [Wild Boar] (*Sus scrofa taiwanus*)	Truku	Taiwan	Food, legends, social practices, spirituality, symbolic value	Simon (2013)
	Beluga (*Delphinapterus leucas*)	Qeqertarsuaq Inuits (Disco Island)	Greenland	Celebrations, Economy, food, identity, social practices	Sejersen (2001); Tejsner (2014)
		Inuvialuit (Western Arctic Inuit)	Canada	Economy, food, social practices	Loseto et al. (2018); Tyson (2017)
		Nunavik Inuit (Northern Quebec)	Canada	Cosmology, economy, food, social practices	Tyrrell (2008)
	Bush buck (*Tragelaphus scriptus*)	Ikoma and Natta (Serengeti District)	Tanzania	Sacred species, symbolic value	Kideghesho (2008)
	Caribou [Barren-ground caribou] (*Rangifer tarandus groenlandicus*)	Inuvialuit	Canada	Food, fur, social practices	Tyson (2017)
	Caribou [Woodland caribou] (*Rangifer tarandus*)	Gwich'in, Tlicho, Denesuline, and Inuit	Canada	Economy, food, identity, spirituality	Prowse, Furgal, Wrona, and Reist (2009)
	Collared Peccary (*Pecari tajacu*)	Mayan and mestizo peoples of the Lacandon Rainforest (Chiapas)	Mexico	Food, medicine, narratives	García del Valle et al. (2015)
	Cow (*Bos taurus indicus*)	Meena, Bhils, and Kathodi (Rajasthan)	India	Magical-spiritual use; sacred species	Kushwah, Sisodia, and Bhatnagar (2017)
	Deer [Common deer] (*Mazama gouazoubira*)	Chapada do Araparipe villagers (Ceará)	Brazil	Food, medicine, symbolic value	Bonifácio, Freire, and Schiavetti (2016)
	Deer [White-tailed deer] (*Odocoileus virginianus*)	Mayan and mestizo peoples of the Lacandon Rainforest (Chiapas)	Mexico	Food, medicine, narratives	García del Valle et al. (2015)
	Dugong (*Dugong dugon*)	Aboriginal peoples of the Hope Vale community (Cape York Peninsula)	Australia	Food, identity, social practices, symbolic value	Nursey-Bray (2009); Nursey-Bray, Marsh, and Ross (2010)
		Torres Strait islanders	Australia	Celebrations, ceremonies, food, social practices	Butler et al. (2012); Delisle, Kiatkoski Kim, and Stoeckl (2018); Kwan, Marsh, and Delean (2006); Marsh, Grayson, Grech, Hagihara, and Sobtzick (2015)
	Elephant (*Loxodonta africana*)	Ikoma and Natta (Serengeti District)	Tanzania	Sacred species, symbolic value	Kideghesho (2008)
	Gorilla [Cross River gorilla] (*Gorilla gorilla diehli*)	Villagers around Bechati-Fossimondi-Besali forest (Lebialem Division)	Cameroon	Narratives, medicine, symbolic value (totem)	Etiendem, Hens, and Pereboom (2011)

(Continues)

TABLE 2 (Continued)

CIS general group	CIS common and scientific names	People[b]	Country/Nation[b]	Local values and uses mentioned[b,c] (listed in alphabetical order)	References[b]
	Hyena [Spoted hyena] (*Crocuta crocuta*)	Ikoma and Natta [clans: Abhaghetigha and Abasaye] (Serengeti District)	Tanzania	Sacred species, symbolic value	Kideghesho (2008)
	Ibex (*Capra sibirica*)	Western Pamir	Tajikistan	Clothes, folklore, food, materials, symbolic value	Jackson and Jain (2006)
	Fin whale (*Balaenoptera physalus*)	Inuit	Greenland	Economy, food, social practices	Caulfield (1997)
	Leopard (*Panthera pardus*)	Natta [Abasaye clan] (Serengeti District)	Tanzania	Sacred species, symbolic value	Kideghesho (2008)
	Lion (*Panthera leo*)	Ikoma [some Abharanche clans] (Serengeti District)	Tanzania	Sacred species, symbolic value	Kideghesho (2008)
	Marco Polo sheep (*Ovis ammon polii*)	Kyrgyz (Eastern Pamir)	Tajikistan	Clothes, folklore, food, materials, symbolic value	Jackson and Jain (2006)
	Minke whale (*Balaenoptera acutorostrata*)	Inuit	Greenland	Economy, food, social practices	Caulfield (1997)
	Moose (*Alces alces*)	Dene, Cree, and Métis (Fort McCay, Alberta)	Canada	Food, technology	Garibaldi (2009)
		Aboriginal peoples from Yukon	Canada	Economy, food, recreational value, spiritual value	Jung, Czetwertynski, and Schmiegelow (2018)
	Monkey [any species, or specifically tantalus monkey, mona monkey and/or Sclater's monkey, depending on the community] (*Chlorocebus tantalus*, *Cercopithecus mona*, *Cercopithecus sclateri*)	Igbo (Lagwa and Akpugoeze villages, in Imo and Enugu States)	Nigeria	Folklore, identity, narratives, sacred species, symbolic value	Baker, Tanimola, Olubode, and Garshelis (2009); Baker (2013)
	Monkey [mainly spider monkey and woolly monkey] (*Ateles paniscus*, *Lagothrix lagothricha*)	Matsigenka (Manu biosphere Reserve)	Peru	Beliefs, food, identity, narratives, social practices	Shepard (2002)
	Narwhal (*Monodon monoceros*)	Nunavut Inuits	Canada	Economy, food, social practices, source of ivory	Diduck et al. (2005)
		Qeqertarsuaq Inuits (Disco Island)	Greenland	Economy, food, social practices	Tejsner (2014)
	Paca (*Cuniculus paca*)	Mayan and mestizo peoples of the Lacandon Rainforest (Chiapas)	Mexico	Food, medicine, narratives	García del Valle et al. (2015)

(Continues)

TABLE 2 (Continued)

CIS general group	CIS common and scientific names	People[b]	Country/Nation[b]	Local values and uses mentioned[b,c] (listed in alphabetical order)	References[b]
	Polar bear (*Ursus maritimus*)	Inuit (Nunavut)	Canada	Cosmology, economy, food	Freeman and Wenzel (2006); Wenzel (2005)
	Tiger [Bengal tiger] (*Panthera tigris tigris*)	Meena, Bhils, and Kathodi (Rajasthan)	India	Magical-spiritual use; sacred species	Kushwah et al. (2017)
Mollusk	Abalone (*Haliotis* spp.)	Māori	New Zealand	Food, identity, medicine, social practices, spirituality, symbolic value	Mccarthy et al. (2014)
		Gitga'at (British Columbia)	Canada	Food, identity	Garibaldi and Turner (2004)
	Cockle [Basket cockle] (*Clinocardium nuttallii*)	Gitga'at (British Columbia)	Canada	Food, identity	Garibaldi and Turner (2004)
	Cockle [Mangrove cockle] (*Anadara tuberculosa*)	Isla Costa Rica villagers (El Oro)	Ecuador	Economy, food	Beitl (2011)
	Cockle [New Zealand cockle] (*Austrovenus stutchburyi*)	Puketeraki and Ōtakou Marae	New Zealand	Food, identity, symbolic value	Mccarthy et al. (2014)
	Mussel [Green Lipped Mussel] (*Perna canaliculus*)	Māori	New Zealand	Economy, food, social practices	Paul-Burke, Burke, Bluett, and Senior (2018)
	Mussel [New Zealand freshwater mussel] (*Echyridella menziesi*)	Māori	New Zealand	Ceremonies, food, medicine, spirituality, tools	McDowall (2002); Noble et al. (2016)
	Oyster (*Crassostrea virginica*)	Chesapeake Bay coastal communities	USA	Economy, food	Paolisso and Dery (2010)
Reptile	Snake [Cobra, Green mamba, Python and/or Puffadder] (*Naja haje, Dendroaspis angusticeps, Python spp, Bitis arietans*)	Ikoma [clans: Wahikumari, Abharanche, Abhaghetigha, Abhamwancha and Abhahimurumbe] (Serengeti District)	Tanzania	Sacred species, symbolic value	Kideghesho (2008)
	Tortoise [Leopard tortoise] (*Geochelone pardalis*)	Natta [Abasaye clan] (Serengeti District)	Tanzania	Sacred species, symbolic value	Kideghesho (2008)

(Continues)

TABLE 2 (Continued)

CIS general group	CIS common and scientific names	People[b]	Country/Nation[b]	Local values and uses mentioned[b,c] (listed in alphabetical order)	References[b]
	Turtle [Green turtle] (*Chelonia mydas*)	Torres Strait islanders	Australia	Celebrations, ceremonies, food, social practices	Butler et al. (2012); Delisle et al. (2018); Johannes and MacFarlane (1993)
		Aboriginal peoples of the Hope Vale community (Cape York Peninsula)	Australia	Food, identity, social practices, symbolic value	Nursey-Bray (2009); Nursey-Bray et al. (2010)
		Miskitu	Nicaragua	Economy, food, leather, oil, social practices	Lagueux (1998); Nietschmann (1974)
		Bahía Magdalena villagers (Pacific side)	Mexico	Celebrations, food, medicine	Nichols, Bird, and Garcia (2000)
		Seri (Sonoran coast and islands of the Gulf of California)	Mexico	Food, legends, symbolic value	Nabhan, Govan, Eckert, and Seminoff (1999)
		Coastal and island villagers	Papua New Guinea	Celebrations, ceremonies, economy, food, legends, symbolic value, social practices, tools	Spring (1981,1979)
	Turtle [Hawksbill turtle] (*Eretmochelys imbricata*)	Solomon Islands villagers (Melanesia)	Solomon Islands	Food, economy	Hamilton et al. (2015)
	Turtle [Leatherback turtle] (*Dermochelys coriacea*)	Kei Island villagers (Maluku)	Indonesia	Food, social practices	Suarez and Starbird (1995)
	Turtle [Olive ridley turtle] (*Lepidochelys olivacea*)	Ostional villagers (Nicoya Peninsula)	Costa Rica	Aphrodisiac, food, local economy	Campbell (1998,2003)
	Turtle [Sea Turtles] (no specific species)	Wayuú (Guajira Peninsule)	Colombia and Venezuela	Ceremonies, food, legends, medicine, spiritual value, symbolic value	Barrios-garrido (2018a, 2018b)
		Caroline Islands villagers	Micronesia	Ceremonies, food, social practices, symbolic value	McCoy (1995)
		Dangme and Fante (Ada Peninsula and Winneba)	Ghana	Legends, sacred species	Alexander, Agyekumhene, and Allman (2017)

Note: Species are listed in alphabetical order of their general taxonomic group (bird, crustacean, fish, mammal, mollusk, reptile) and then of their common name.

[a]This table does not provide a comprehensive compilation of CIS examples from around the world, but a list of examples found in our search (see Methods section) in order to illustrate the wide range of species that are highly relevant to different peoples worldwide.

[b]The information about each species came from the studies found in our search (see Methods section) and do not necessarily correspond to all data available to the species (ie. to its whole geographic distribution, to all the cultures linked to the species, to all local uses and values, or to all references about the species and its cultural importance).

[c]All species included in this table were clearly mentioned to be highly culturally important to local people. The number of uses/values listed in the table does not necessarily correspond to the degree of the species' cultural importance.

[Correction added on 13 May 2020, after first online publication: the information on 'Bush buck' has been moved to the 'Mammal' section within the table in this version.]

5.1 | Key learnings

5.1.1 | Learning from similarities between the case studies

The strong connection local people have with a species tends to promote a deep cultural incentive to seek the recovery of its population to sustainable levels, which stimulates communal engagement and continued on-the-ground enforcement of conservation practices related to the species. The two case studies addressed here are real examples of that, and in both cases local engagement was so effective that it has become the strongest predictor of *Arapaima* spp. and *Podocnemis* spp. abundance across multiple contexts (Campos-Silva et al., 2018; Campos-Silva & Peres, 2016; Miorando et al., 2013). Indeed, if local people are thoroughly engaged in a certain initiative, there is better potential for full-time physical presence and effective local surveillance, as they are residents in the target areas (Jentoft et al., 1998; Ostrom, 2007; Pomeroy, Katon, & Harkes, 2001). Even though kinship ties may represent a barrier for local sanctions (Crawford, Siahainenia, Rotinsulu, & Sukmara, 2004), peer pressure and moral obligation are often stronger determinants of people's behaviour than formal rules, especially in places where official surveillance is low or non-existent (Crawford et al., 2004; Kaplan, 1998; Sutinen & Kuperan, 1999).

Despite having a CIS in focus, CIS-management schemes are not supposed to concentrate on benefiting the target species only. Instead, the initiatives should be based on rules that embrace the ecosystem scale and ensure direct benefits to various co-occurring non-target taxa. This is exactly the case in both *Arapaima* spp. and *Podocnemis* spp. management schemes (Table 1) – whereas the former is grounded on the zoning of the water bodies, including no-take lakes, the latter is centered on the protection of the entire fluvial beach. Therefore, these management initiatives could be considered examples of Ecosystem-Based Management (EBM; Pikitch, 2004). Similar management schemes, focusing on CIS but grounded on procedures aimed at protecting the entire ecosystem, would be strongly advised to other contexts as well. The focus on CIS may be a trigger to spark local people's motivation and real engagement in EBM schemes.

The establishment of a spatial zoning based on a source-sink model is also strongly advised for CIS-management initiatives, since it enables the species to recover in no-take areas and spill-over to other areas (Campos-Silva, Peres, Antunes, Valsecchi, & Pezzuti, 2017; Di Lorenzo, Claudet, & Guidetti, 2016; Stobart et al., 2009), as it happens in the *Arapaima* spp. and *Podocnemis* spp. managements. It is also important to design monitoring strategies aiming at verifying population trends over time. Quantitative studies are especially advantageous in this case, as they enable following up on the changes in an objective way, comparable at both temporal and spatial scales, and may also be useful to avoid misinterpretations of the stocks condition due to the 'shifting baseline syndrome' (sensu Pauly, 1995). Yet, community-based monitoring should be prioritized, as local people are an essential part of the scheme, and ought to be empowered and recognized as protagonists, and duly rewarded for their efforts.

5.1.2 | Learning from differences between the case studies

Income generation viability may be a relevant factor to ensure the long-term sustainability of any management initiative (Pomeroy et al., 2001). Some people might be interested in a certain initiative due to cultural or moral motivation only, and be willing to sacrifice income or incur personal costs to carry out a moral duty (Sutinen & Kuperan, 1999). This is the case of the turtle management scheme, for example, in which community ethics and emotional connection with *Podocnemis* spp. are the main motivations for local engagement (Pezzuti et al., 2018; Table 1). Nevertheless, motivations can change over time. Indeed, many beach guards anticipate that social and market pressures might have a negative effect on beach guards' long-term engagement with beach protection, or on their replacement by future generations (Campos-Silva et al., 2018). If a beach guard gives up or has no successor, all the conservation gains made over the years can be quickly lost. In contrast, in the arapaima co-management, sales of sustainably harvested fish bring direct economic benefits for many families in the community, which entails compliance and long-term engagement among the entire fishing village, and encourages community-led surveillance and widespread peer pressure. Finding ways of generating income from any CIS-management may enhance communal involvement and long-term commitment with the scheme, reduce poaching, and make the activity less vulnerable to oscillations in political interests and external support.

Yet, the striking financial contrast between our two case studies is consequence of an intrinsic difference between them: while national legislation prevent turtle harvesting in Brazil, specific legal norms allow regulated arapaima trade (e.g. Acre Normative Instruction N° 01, 30th May 2008; Amazonas Normative Instruction N° 1, 1st June 2005; Rondônia Normative Instruction N° 2, 13th May 2019). Even though delayed sexual maturity may impose higher vulnerability to the exploitation of turtle's juveniles and adults (Thorbjarnarson, Lagueux, Bolze, Klemens, & Meylan, 2000), a recent study focusing on *P. unifilis* showed that increasing first-year survival could generate rapid population increases and even compensate for population losses due to adult harvesting (if adult female harvest remains <25%; Norris, Peres, Michalski, & Gibbs, 2019). Studies have also shown that the sustainable harvest of turtle eggs can represent a viable management alternative (Alho, 1985; Campbell, 1998; Caputo, Canestrelli, & Boitani, 2005; Escalona & Fa, 1998; Pezzuti & Vogt, 1999), especially in places where a high proportion of nests is normally lost for natural causes, as in many Amazonian fluvial beaches (Caputo et al., 2005; Pezzuti & Vogt, 1999). Scholars have advocated that arrangements enabling regulated turtle harvest may be the most effective way to ensure the long-term conservation of *Podocnemis* spp. in the Amazon, considering the current scenario of deficient enforcement associated with high levels of illegal harvest (Alho, 1985; Campos-Silva et al., 2017, 2018; Pezzuti et al., 2019; Pezzuti & Vogt, 1999). Similar to the Amazonian turtle case, other CIS-managements worldwide can find analogous obstacles, and efforts may be needed to overcome them.

The role of education and outreach is another important aspect to be considered in any CIS-management initiative. A striking difference between our two case studies reinforce this point. While arapaima co-management has been acclaimed by the media, the government and NGOs, and there is a widely built perception that the scheme is fruitful for the community and relevant to conservation (CTF and JVCS personal observation), beach protection is a neglected initiative with little public profile throughout the region, despite its long history and great importance (Pezzuti et al., 2018; Table 2). Such lack of societal appreciation, together with the poor financial viability of the initiative, might lead to its future failure, as anticipated by many beach guards (Campos-Silva et al., 2018). We advocate that CIS-management initiatives worldwide should consider the relevance of formal recognition as a way to stimulate local engagement and peer pressure, since it reinforces the wide collective perception that the scheme is beneficial and therefore morally and ethically defensible (Crawford et al., 2004).

5.2 | CIS-management and its applicability to multiple contexts worldwide

The extensive variety of CIS existing worldwide, partially demonstrated on Table 2, awakens us to the possibility of motivating the establishment of CIS-management initiatives across various contexts. Yet, when designing a CIS-management proposal it is indispensable to analyse the singularities of each reality. The cultural importance of a species is always context-dependent, and a certain species that is highly important to one group may not be to another, even if both groups are in contact with the same species (Garibaldi & Turner, 2004). The relevance and uses of a species may also change over time, as cultures are dynamic and adaptive (Cristancho & Vining, 2004). Furthermore, each ecosystem will function in a particular way (and also change over time), and rules or strategies operating in one place may not be suitable to another, even if the target species are the same. Developping CIS-management proposals in close partnership with local people is therefore crucial to ensure that the proposed scheme is culturally, socially and ecologically relevant and approriate, in addition to being flexible to changes. However, it is important to evaluate the impact that the target CIS may have on the natural ecosystem functioning, avoiding efforts to support eventual non-native species that have become a CIS (Nuñez & Simberloff, 2005).

The general steps and feed processes expected to be found in any CIS-management initiative are outlined as a flow chart in Figure 4. The process illustrated in this figure can be briefly described as following: an ecosystem-based co-management scheme with a focus on CIS will likely arouse local people interest on the initiative, stimulating their engagement (Figure 4). Such engagement will likely result in local compliance and surveillance, and consequently bring dividends to ecosystem conservation and species recovery. Species recovery will likely generate direct and indirect ecological, cultural, social, and economic benefits, which may reinforce local people interest in the initiative, resulting in further reinforcing feedback to the system (Figure 4).

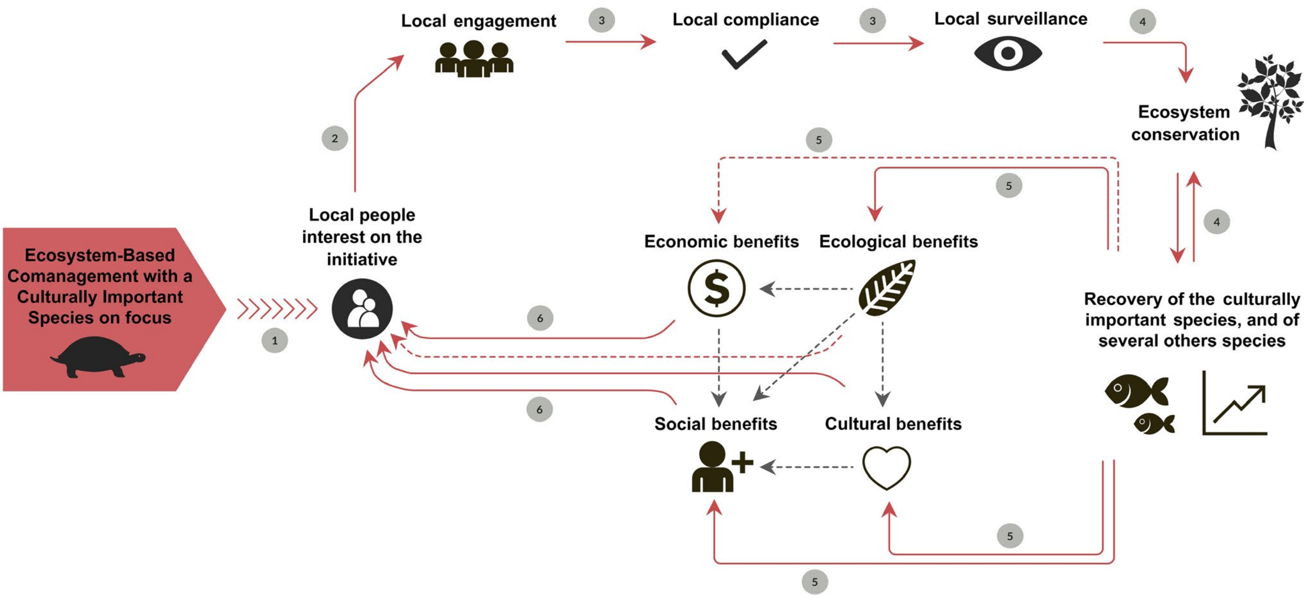


FIGURE 4 Flow chart representing steps and feed processes expected to be found in any conservation initiative focusing on Culturally Important Species (CIS). Continuous lines indicate processes very likely to happen, while dashed lines indicate processes that may happen depending on the context. In general, the flow chart shows that (1) ecosystem-based co-management schemes focusing on a CIS will likely arouse local people interest on the initiative; (2) once local people are interested, they will be keen to get engaged on it, which will likely result in (3) local compliance and surveillance, and consequently bring dividends to (4) ecosystem conservation and species recovery. Species recovery will likely (5) bring direct and indirect ecological, cultural, social, and economic benefits, which will (6) reinforce local people interest in the initiative, resulting in further reinforcing feedback to the system [Colour figure can be viewed at wileyonlinelibrary.com]

As such, management schemes focusing on CIS may trigger positive socio-ecological consequences at multiple scales in many different contexts throughout the world. The positive impact of CIS-management may be especially meaningful in developing countries, where not only official enforcement tends to be weak or non-existent (Berkes et al., 2001; Campos-Silva et al., 2015), but also corruption tends to be high (Transparency International, 2018). The common mismanagement of public finances and/or bribery of officials, frequently happening in these countries, further aggravates difficulties in implementing effective enforcement schemes (Agnew et al., 2009; Smith, Muir, Walpole, Balmford, & Leader-Williams, 2003). Therefore, triggering local people interest and consequent engagement on conservation initiatives may often be the best solution for ensuring the perpetuation of local natural resources.

6 | CONCLUSIONS

The cultural importance of any given species should be regarded as a highly relevant aspect in conservation strategies designed for areas where natural resource use is critical to local livelihoods. Given that local people have the most to gain from CIS population recovery, management initiatives focusing on those species have a strong potential to stimulate local people interest, and their consequent engagement, compliance and enforcement. Such local, full-time surveillance is potentially much more effective than official mechanisms of institutional enforcement, which are typically deficient and deployed sporadically, especially in countries with low governance levels. Importantly, the proposed focus on CIS does not mean that the management initiatives should be designed to benefit the target species only. We advocate management schemes with rules embracing the ecosystem scale and ensuring that many other species, and the environment as a whole, will also benefit from the conservation initiative. The focus on CIS may be a trigger to spark local people's motivation and real engagement in the conservation scheme. As such, the scheme will likely achieve a wide range of positive ecological, social, cultural and economic outcomes. Therefore, we claim that CIS-management can be an effective socio-ecological tool to reconcile biodiversity conservation with local people quality of life, keeping with the Sustainable Development Goals set out by the United Nations to guide developing policies (United Nations, 2015).

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHORS' CONTRIBUTIONS

C.T.F. conceived the central idea, did the literature review, and drafted the manuscript; P.F.M.L., J.V.C.S., M.M.N., R.B. and C.A.P. gave critical suggestions for its content and design, and revised it critically; M.M.N. did the maps. All authors gave final approval for publication.

DATA AVAILABILITY STATEMENT

This manuscript is literature-based. Therefore, the data used have already been published elsewhere. The source for each data is mentioned in the respective citation, and the citation is fully stated in the References section.

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Review of sustainability terms and their definitions

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Abstract

Terminology in the field of sustainable development is becoming increasingly important because the number of terms continues to increase along with the rapid increase in awareness of the importance of sustainability. Various definitions of terms are used by different authors and organizations, for example, green chemistry, cleaner production, pollution prevention, etc. The importance of this topic has stimulated research into the problems of clarifying ambiguity and classifying terms used in the sustainability field. This paper provides results of the literature survey and summarizes the definitions of the terms, focusing on the environmental engineering field. In some cases, it proposes an improved definition. A hierarchical classification of the terms and their relationships has been based on a layer format that is presented graphically.

Keywords: Sustainability; Cleaner production; Terminology; Definitions; Classification

1. Introduction

The recent research and growth of knowledge about sustainable development have increased interest in sustainable development terminology, which has gained prominence over the past decade. It embraces terms such as cleaner production, pollution prevention, pollution control, and minimization of resource usage, eco-design and others. These terms are in common use in scientific papers, monographs, textbooks, annual reports of companies, governmental policy usage, and the media. Application of terms depends on their designation and recognition, rather than on domain concept. Yet, some of the terms are specific, permitting differentiation from the others. Also, differences amongst term usages, based upon geographical area, exist that often lead to imprecise definitions of the terms and their usage.

The availability of various information sources increases the spread of sustainability terms and their definitions, as employed by different authors and organizations. As a consequence, numerous new terms are emerging, or the existing ones are being extended in the sustainability field, but not enough critical attention has been given to the definitions and their semantic meanings. The multitude of definitions causes much confusion about their usage, since the meaning of some terms is either sloppy or similar, or is only slightly different from one another.

Another important issue is that most of the terms are multi-word units and, therefore, the definitions are unavailable in dictionaries. To our knowledge, this topic has not been analysed, yet. Semantics and content analysis enable the researcher to better describe and understand sustainable development concepts. Consequently, communications within the scientific community, organizations, agencies and stakeholders can be improved. A hierarchical classification and relationship of the terms needs to be developed in order to achieve better and easier understanding.

Much of this research was devoted to a survey of literature and Internet sources, comprising the terms and definitions associated with the sustainable development field. Therefore, the terminology is based upon usage within the United Nations Environment Programme (UNEP), the U.S. Environmental Protection Agency (EPA), the European Environmental

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Agency (EEA), the Organization for Economic Co-operation and Development (OECD), the Journal of Cleaner Production, and others.

The survey revealed that definitions used to describe a concept might be non-specific and the terms could be understood ambiguously.

Therefore, this research was designed to develop a framework for improved, coherent, and sustainable terminology, providing enough freedom to make clear distinctions to spur research in this field for developing the basic terms, thus allowing the terminology to be further advanced. An important reason for this research was that sustainable development should be supported by a common, unambiguous terminology, applicable to real-world problems.

2. Terminology

Terminology represents an integrated framework for all related terms and serves as a basis for communication within a particular scientific field. In addition, in sustainable development, various terms are used to describe different strategies, actions, effects, phenomena, etc. Movement from usage of inappropriate terms and unambiguous definitions can help us to make more rapid progress in sustainable development science and engineering. In this research, special attention has been given to terms connected with the environmental engineering field. Fifty-one selected terms were investigated: a semantic analysis of these terms and their definitions were performed. First, the terms were identified, and the content of their definitions was analysed. Then, improved definitions have been proposed in some cases.

Our classification framework uses a '*system's approach*'. The systems consist of simple elements (principles): *Environmental/Ecological, Economic, and Societal Principles*. These elements are followed by *Environmental Approaches (Tactics)* and *Environmental Sub-systems (Strategies)*. The broader term embracing principles, approaches and sub-systems is labelled as *Sustainable System*. Therefore, the system is treated as a hierarchical structure of principles, approaches and sub-systems. The term *tool*, used to further realization of principles, approaches, sub-systems, systems and policy, is not included into systems.

3. Definitions of principles: an overview

As used in this text, *principles* are fundamental concepts that serve as a basis for actions, and as an essential framework for the establishment of a more complex system. Semantically, principles are narrow and refer only to one activity or method. They provide guidance for further work and, therefore, occupy the lowest position in the hierarchy. We have positioned the principles within environmental and ecological, economic, and societal dimensions (Fig. 1).

There are only a few one-dimensional principles, situated at the vertices of the base. Principles having two dimensions of sustainable development are placed along a side of the triangle. Principles situated in the plane, directly or indirectly, include all the three dimensions. Three-dimensional principles can serve as a basis for building a more complex system − *Sustainable system.*

3.1. Environmental principles

Environmental principles denominate those terms that describe environmental performance, in order to minimize the use of hazardous or toxic substances, resources and energy. These terms are: *renewable resources*, *resource minimization*, *source reduction (dematerialization)*, *recycling*, *reuse*, *repair*, *regeneration*, *recovery*, *remanufacturing*, *purification, end-of-pipe*, *degradation*, and are arranged from preventive to control principles.

3.1.1. Renewable resources

Renewable resources *are available in a continually renewing manner, supplying materials and energy in more or less continuous ways. In other words, renewable resources do not rely on fossil fuels of which there are finite stocks* [1]. The term emerged as a response to increased carbon dioxide emissions. It is fostered by the rise of the sustainability paradigm and includes energy resources such as solar, wind, tidal, wood, biomass, and hydroelectric. Of course food and feed are renewable resources as well.

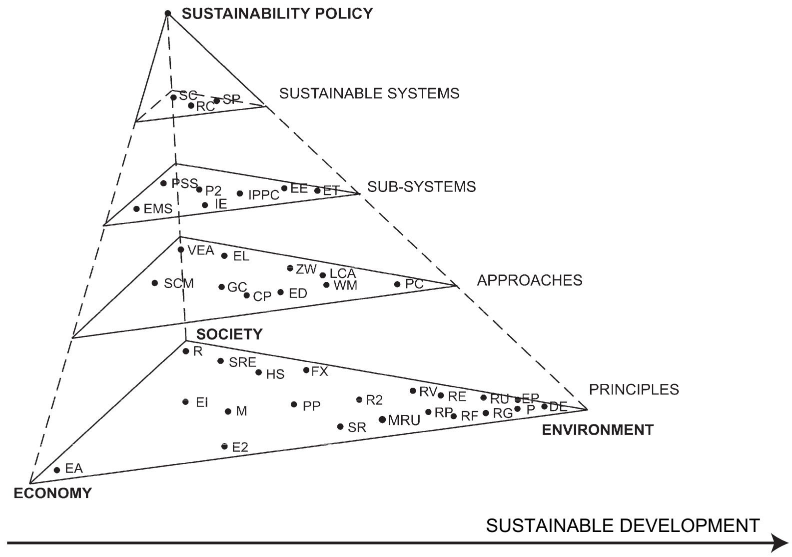
3.1.2. Minimization of resource usage

The fact that natural resources will not last forever is leading to widespread concerns about energy, raw materials and water supply. Therefore, a resource minimization principle has been developed. The definition of the term has not been proposed, yet.

Minimization of resource usage is understood as *conservation of natural resources*. It is an activity that can be applied to any reduction of usage of resources. Therefore, the term encompasses not only raw materials, water, and energy, but also applies to natural resources such as forestry, watersheds, other habitats, hunting, fishing, etc. All these resources and processes which enable ecosystems to survive and are essential for helping societies to make progress toward sustainability must be addressed. Thus, resources can be conserved, their availability improved and maintained. Reduction in the usage of materials and energy can result in dramatic cost savings.

3.1.3. Source reduction (dematerialization)

Source reduction is *the practice that reduces the quantity of materials entering a waste stream from a specific source by redesigning products or patterns of production and consumption* [2]. Besides materials, this definition also encompasses energy. According to the EPA **dematerialization** refers to *quantitative reduction in the volume of material and energy used to meet user's demand, while maintaining a uniform quality of services* [3] and as introduced by Wernick et al., it *refers to the absolute or relative reduction in the quantity of materials required to serve economic functions and matters for the environment* [4]. This definition of materialization



CP, cleaner production; DE, degradation; EA, environmental accounting; ED, eco-design; EE, environmental engineering; EI, ethical investment; EL, environmental legalisation; EMS, environmental management strategy; ET, environmental technology; E2, eco-efficiency; F*X*, factor *X*; GC, green chemistry; HS, health and safety; IE, industrial ecology; IPPC, integrated pollution prevention and control; LCA, life cycle assessment; M, mutualism; MRU, minimization of resource usage; P, purification; PC, pollution control; PO, policy; PP, "polluter pays" principle; PSS, product service system; P2, pollution prevention; RC, responsible care; R, reporting to the stakeholders; RE, recycling; RF, remanufacturing; RG, regeneration; RP, repair; RU, reuse; RV, recovery; R2, renewable resources; SC, sustainable consumption; SCM, supply chain management; SD, sustainable development; SP, sustainable production; SR, source reduction; SRE, social responsibility; VEA, voluntary environmental agreement; WM, waste minimization; and ZW, zero waste.

Fig. 1. Classification of sustainability oriented terms.

is more appropriate, because dematerialization is semantically not applicable to energy.

Source reduction contributes to a lowering of disposal and handling costs, because it avoids the costs of recycling, municipal composting, landfilling, and combustion. Source reduction also conserves resources and reduces pollution, including greenhouse gases that contribute to global warming [2].

3.1.4. Recycling, reuse, repair

The **recycling** is defined as *a resource recovery method involving the collection and treatment of waste products for use as raw material in the manufacture of the same or a similar product* [1]. The EU waste strategy distinguishes between reuse and recycling. The **reuse** *means using waste as a raw material in a different process without any structural changes* and **recycling** *refers to structural changes in materials within the same process* [1]. **Repair** *means an improvement or complement of a product, in order to increase quality and usefulness before reuse*; it decreases consumption, because the product's life is extended.

3.1.5. Regeneration, recovery, remanufacturing

Regeneration is *an activity of material renewal to return it in its primary form for usage in the same or a different process*. This activity enables an internal restoration and, therefore, decreases the environmental impacts. **Recovery** is an *activity applicable to materials, energy and waste. It is a process of restoring materials found in the waste stream to a beneficial use which may be for purposes other than the original use* [1], e.g. resource recovery in which the organic part of the waste is converted into some form of usable energy. Recovery may be achieved by combustion of a waste material in order to produce steam and electricity, or by a pyrolysis of refuse to produce oil or gas, or by anaerobic digestion of organic wastes to produce methane gas and a fermentate that can be used as a soil-conditioner [1]. **Remanufacturing** is defined as *substantial rebuilding or refurbishment of machines, mechanical devices, or other objects to bring them to a reusable or almost new state*. This prevents many reusable objects from becoming waste. The remanufacturing process usually involves disassembly, and frequently involves cleaning and rebuilding or replacing components. Remanufactured objects are sometimes referred to as rebuilt objects [5].

3.1.6. Purification and end-of-pipe

Purification is *the removal of unwanted mechanical particles, organic compounds and other impurities*. The process of removal could be mechanical, chemical or biological in order to improve the environment and quality of life. **End-of-pipe** is defined as *a practice of treating polluting substances at the end* *of the production process when all products and waste products have been made and the waste products are being released (through a pipe, smokestack or other release point)* [3]. This approach is designed to reduce the direct release of pollutants so as to achieve compliance with environmental regulations; sometimes it results in transmitting pollutants from one medium to another. Therefore, it can result in only a temporary delay of causing environmental problems.

3.1.7. Degradation

Term **degradation** could be understood as *a biological, chemical or physical process, which results in the loss of productive potential* [1]. From the biological point of view, degradation can lead to the elimination and extinction of living organisms. It can also refer to biological degradation of plant and animal residues, thereby making their elemental components available for future generations of plants and animals.

3.2. Ecological principles

Industrial and all other human systems have their origin in natural systems that must obey natural laws. The most important feature of natural systems is their interconnection. **Ecological principles** have to be considered in order to understand the relationships between natural ecosystems. These principles are essential for the interaction of various systems. Every sub-system in nature is linked with every other subsystem through indirect or direct interconnections. In the natural ecosystem, many relationships exist between species, each with different consequences. Among the possible interrelationships, the following are the most common:

- *competition*: influences the species in a negative way and none of the species benefits; the main objective is the elimination of other species from an ecological niche;
- *predatory*: one species ''eats'' the prey; the predator has the benefit;
- *amensalism*: one species is impaired and the other is neither positively nor negatively affected;
- *parasitism*: one species benefits and the other is impaired;
- *neutralism*: a hypothetical category where one species does not harm or benefit the other species;
- *commensalism*: one species receives benefits and the other is not impaired;
- *protocooperation*: both interrelated species receive conditional benefits, but they can survive separately; and
- *mutualism*: both species receive benefit.

The last three relationships are understood as symbiosis, because systems are either not impaired or receive benefits due to the interactions.

In the industrial environment, similar relationships are being documented and developed. Industrial symbiosis seems to be the most common of all the existing relationships, but a more appropriate term may be 'industrial mutualism', where the involved subjects (enterprises, employees, and community) live together and all of them enjoy benefits. Such relationships present an obligation for all the subjects involved, allowing better utilization of resources and energy; thus resulting in increased probability of survival. The key issues of industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity [6].

3.3. Economic principles

Economic principles embrace terms like *Environmental Accounting, Eco-efficiency (Factor X, Factor 4, and Factor 10), and Ethical Investments.*

3.3.1. Environmental accounting

Environmental accounting *is designed to bring environmental costs to the attention of the corporate stakeholders who may be able and motivated to identify ways of reducing or avoiding those costs while at the same time improving environmental quality and profitability of the organization* [2]. Environmental accounting can be applied at the national, regional and corporate levels. National accounting refers to physical and monetary accounts for environmental assets and the costs of their depletion and degradation. Corporate environmental accounting refers to environmental auditing, but may also include the costing of environmental impacts caused by the corporation [1].

3.3.2. Eco-efficiency

The term Eco-efficiency was perceived within numerous definitions of cleaner production. [7]. **Eco-efficiency** is *the delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life cycle, to a level at least in line with the earth's estimated carrying capacity* [3,15]. It is based on the concept of ''doing more with less'' [8] representing the ratio between economy and environment, with the environment in the denominator [7]. It is about more efficient use of materials and energy in order to provide profitability and the creation of added value. In the triangle, it could be located at the side between the economic and environmental dimensions. According to the usual usage, eco-efficiency specifically emphasizes production processes and services.

3.3.3. Factor X, Factor 4, and Factor 10

Robert et al. [9] defined **Factor *X*** as *a direct way of utilizing metrics in various activities that can reduce the throughput of resources and energy in a given process.*

The Factor *X* concept is a very useful and flexible approach for monitoring activities aimed at reducing the materials and energy usage of diverse industrial and societal processes [9]. The overall aim of Factor *X* is to enable society to achieve the same or even better quality of life improving human welfare, while using significantly less resource inputs and causing less ecosystem destruction. The Factor *X* concept proposes *X* times more efficient use of energy, water and materials in the future as compared to the usage today. In other words, **Factor 4** refers to *a fourfold increase in resource productivity*;

Factor 10 refers to *a tenfold increase in productivity* [10,11]. These approaches are societally and environmentally oriented, and are therefore, located at the side between these two dimensions.

3.3.4. Ethical investments

Ethical investments or **socially responsible investments** are *financial instruments (mortgages, bank accounts, investments, utilities, and pensions), favouring environmentally responsible corporate practices and those, supporting workforce diversity as well as increasing product safety and quality* [12,13].

3.4. Societal principles

Societal principles are composed of terms such as *Social Responsibility, Health and Safety, ''Polluter pays'' principle (Taxation)*, and *Reporting to the stakeholders*.

Social responsibility refers to *safe, respectful, liberal, equitable and equal human development, contributing to humanity and the environment*. Furthermore, the term **health and safety** usually refers to *the working environment and includes responsibilities and standards*.

The **Polluter pays principle** was defined by the EEA [1] as *a principle that those causing pollution should pay the costs it causes*. Thus, the polluter pays for environmental damage in the form of a clean-up or taxation but usually, in practice, this principle is overlooked.

Reporting to the stakeholders is about *sharing the progress, results and planning with the general public*. The leading role has been taken by Global Reporting Initiative, presenting global effort to create a framework for reporting on economic, environmental and social performance by all organizations [14].

4. Definitions of approaches

Approaches (tactics) contain a group or cluster of principles related to the same topic, building a more complex system. Approaches are semantically broader than principles and they are organized within environmental, economic and societal dimensions. Strictly one-dimensional approaches do not exist, as in the case of principles. They are connected to all other dimensions of sustainable development.

4.1. Environmental approach

The term environmental approach is a concept-oriented term that encompasses pollution control, cleaner production, green chemistry, eco-design, life cycle assessment, waste minimization, and zero waste. It involves more or less economic and societal content at a higher level of hierarchy as shown in Fig. 1. All the terms incorporate the elementary principles and activities, showing how to apply specific practices in order to contribute to improved industrial performance.

4.1.1. Pollution control

A 'pollution control' definition was not found in the literature examined. The term relates to the past, when pollutants were simply 'managed.' The so-called *end-of-pipe pollution control technologies* utilize pollution control for the management of most problems of waste and emissions of pollutants from industrial sources.

Pollution control can be defined as ''*an approach that is designed to reduce the impacts of pollutants that are produced, before they are released into the environment; this is accomplished by some type of treatment*.'' The pollution control approach focuses upon capturing and treating, rather than reducing the *production of pollutants at their sources* and thus, is a ''react and treat'' approach [15]. It includes end-of-pipe pollution control technologies, emission abatement, purification, and monitoring activities. Consequently the pollutants are often merely transferred from one medium to another and cause additional costs. Since pollution control does not lead to prevention of the production of pollutants at their sources, it is not in accordance with the sustainable development vision.

4.1.2. Cleaner production

The definition of cleaner production has raised a lot of interest during the past decade. This definition was developed by UNEP in Paris in 1989. Since then the definition has been expanded and a sustainable development orientation has been added. For example, a broader vision was established in the year 2004. The direct involvement of the economic dimension ''…by using better management strategies, methods and tools…'' [16,17].

It includes both a condition for achieving environmental improvements in process and product development, and a contribution to a more sustainable world.

Cleaner production management strategies endeavour to:

- increase the productivity of materials;
- improve energy efficiency;
- improve material flow management;
- apply preventive environmental protection approaches;
- strive for sustainable use of natural capital; and
- achieve accordance with legal compliance [17].

These expansions of the cleaner production definition have led to confusion. Therefore, we propose an improved **cleaner production** definition, in order to reduce or prevent ambiguity: *cleaner production is a systematically organized approach to production activities, which has positive effects on the environment. These activities encompass resource use minimization, improved eco-efficiency and source reduction, in order to improve the environmental protection and to reduce risks to living organisms*. It can be applied to processes used in any industrial sector and to products themselves (cleaner products). Although cleaner production, as practiced and taught and underscored by UNEP and UNIDO, includes services, this definition excludes them, because production is understood as output, such as units made in a factory, oil from an oil well, chemicals from a processing plant [18] or the process of growing or making goods or materials [19,20]. On the other hand, service is understood as the performance of maintenance, supply, repair, installation, distribution, and so on, for or upon an instrument, installation, vehicle, or territory [18], or as a system that provides something that the public needs, a business whose work involves doing something for consumers, but not producing goods [19,20]. Therefore, a new term *Cleaner services* should be used.

4.1.3. Eco-design

Terms used for the description and characterization of product and service design are adjusted under the multi-word terms **eco-design** and **design for environment**. Both terms are understood as *a product development process that takes into account the complete life cycle of a product and considers environmental aspects at all stages of a process, striving for products, which make the lowest possible environmental impact throughout the product's life cycle* [3,15]. The inclusion of environmental dimensions in product design and services contributes to product innovations. This term encompasses eco-efficiency, health and safety, remanufacturing, recycling, source reduction, waste minimization and it is linked with life cycle assessment.

4.1.4. Green chemistry

Despite the numerous green chemistry definitions, similarity among them is clearly visible from the semantic point of view. **Green chemistry**, also known as sustainable chemistry, introduces an umbrella concept that has grown substantially since it emerged a decade ago [21]. *Green chemistry is the design of chemical products and processes that eliminate or reduce the use and generation of hazardous substances* [22]. Moreover, green chemistry relies on a set of 12 rules that contain five principles: waste minimization, renewable resources, eco-efficiency, degradation, and health and safety. Therefore, chemical reactions should be designed or modified to be clean and sustainable, while maintaining the current standard of living. Under the green chemistry approach, the reduction of hazardous materials through the selection of feedstocks, reagents, and reaction pathways as well as the use of alternative solvents is emphasized. Green chemistry also includes the use of catalysts to yield desired products by achieving higher selectivity than may have been achieved by previously used catalysts [22].

4.1.5. Life cycle assessment

The term **life cycle** addresses *all stages and the life time of products, their environmental impacts as well as services, manufacturing processes, and decision-making*. It is realized through the life cycle assessment (LCA). Life cycle presents a basis for achieving improved life cycle performance and it is an essential approach for the implementation of sustainable development into product design.

The most precise definition of **life cycle assessment (LCA)** was provided by EPA [2] and EEA [1] as *the method/process for evaluating the effects that a product has on the environment over the entire period of its life, thereby increasing resource-use efficiency and decreasing liabilities*. It can be used to study the environmental impact of either a product or a function the product is designed to perform. LCA is commonly referred to as a "cradle-to-grave" analysis. Its key elements are the following: (1) identify and quantify the environmental loads involved, e.g. the energy and raw materials consumed, the emissions and wastes generated; (2) evaluate the potential environmental impacts of these loads [1]; and (3) assess the options available for avoiding or reducing these environmental impacts.

A more detailed expansion in the second part of the definition may explain that LCA introduces input/output accounting and can be applied to production processes, to products and services or even to strategic planning. A basic step in LCA is an inventory analysis that provides qualitative and quantitative information regarding consumption of material and energy resources (at the beginning of the cycle) as well as releases into the anthroposphere, hydrosphere, geosphere, and atmosphere (during its use or at the end of its life cycle). It is based upon various material cycles and budgets; it quantifies the materials and energy required as inputs, and the benefits and liabilities posed by the products. The related area of impact analysis provides information about the kinds and degrees of environmental impacts resulting from the complete life cycle of the product or activity. After the environmental and resource impacts have been evaluated, it is possible to perform an improvement analysis in order to determine measures that can be taken to reduce impacts on the environment or to reduce resource or energy usage [23]. Thus, LCA includes the life cycle principle and it refers to the supply chain management approach.

4.1.6. Waste minimization

Following EPA, **waste minimization** is defined as *measures or techniques that reduce the amount of wastes generated during industrial production processes* [2]. It is including source reduction or recycling activity undertaken by the generator that results in either (1) a reduction in the total volume of waste, or (2) a reduction in the toxicity of the waste, or (3) both, so long as the reduction is consistent with the goal of minimizing present, and reducing future threats to human health and the environment. It is about minimizing waste at source, recycling, and purifying during the production process. According to the definition, this term is environmentally oriented, and refers to industrial performance. But, the term indirectly refers to the human health and safety dimensions. Due to toxicity and waste minimization, it is also linked to cost and risk reduction.

4.1.7. Zero waste

The definition of **zero waste** was not found among the UNEP, EPA or EEA glossaries, but is defined by the Grass Roots Recycling Network [24] as *a design principle for the 21st century. It includes 'recycling' but goes beyond recycling by taking a holistic approach to the vast flow of resources and waste through human society*. Zero waste maximizes recycling, minimizes waste towards zero, reduces consumption and ensures that products are planned to be reused, regenerated, repaired, and recycled internally or back into nature or the marketplace. Zero waste makes recycling a powerful entry point into the critique of excessive consumption, waste, corporate responsibility, and the fundamental causes of environmental destruction [24]. Furthermore, zero waste does not take into consideration waste as a material that must be disposed off or incinerated, but treats waste as a resource that can be used again and so takes full advantage of the waste potential.

4.2. Economic and societal approaches

In order to understand and make progress toward a sustainable system, economic and societal approaches are also needed. These approaches are of fundamental importance and they embrace the terms: *environmental legalisation*, *voluntary environmental agreements*, and *supply chain management*.

Environmental legalisation *is a set of legal principles, acts, regulations, directives, and laws, influencing both the environment and the inhabitants of each country or union*. The aim of such a system is to improve the environmental protection, and the quality of life.

According to Long and Arnold [25] **voluntary environmental agreements** are defined as *agreements among the corporate, government and/or non-profit sectors, not required by legislation. They present contracts between the public administration and the industry in which the firm agrees to achieve a certain environmental objective and receives a subsidy to change its technology through research, development, and innovation* [1]. The agreement is bilateral, between one party and the administration, and requires a voluntary element on both sides [1]. The aim is to improve the environmental quality and the utilization of natural resources. Voluntary Environmental Agreements could have important influences in our common future as long as they are fostered by local communities, non-governmental organization, and industrial sectors rather than by government.

Supply chain management is defined as *a process of planning, implementing, and controlling the operations of the supply chain with the purpose of satisfying consumer requirements*. Moreover, it spans all transportation and storage of raw materials, work-in-process inventory, and finished goods from point-of-origin to point-of-consumption [26].

5. Definitions of sub-systems: strategies

Sub-systems present parts of a more complex system. Each consists of approaches, connected together; they introduce strategies that are to be met in order to achieve integral conservation of the environment, and contribute to short- and long-term human welfare.

5.1. Environmental sub-systems

The consciousness about human activities and their impacts on the global environment has fostered the implementation of various strategies to prevent environmental degradation. These activities are embraced under the term *Environmental Sub-systems* and are practiced through *Environmental/green technology and engineering*, *Integrated pollution prevention and control*, *Industrial ecology*, and *Pollution prevention*. These strategies are mostly environmentally oriented, but they also include societal and economic dimensions.

5.1.1. Environmental engineering and environmental technology

Particular emphasis should be given to the terms **engineering** and **technology**. While **engineering** encompasses *activities of design and construction, operation and use of techniques*, **technology** deals with *processes and methods of production*.

Environmental (green) engineering can be defined as *the design, construction, operation, and use of techniques, which are feasible and economical while minimizing the generation of pollution at the source and the risk to human health and the environment* [2], and, therefore, includes eco-design, LCA, and green chemistry. Environmental engineering focuses on achieving sustainability through the application of science and technology [22]. On the other hand, **environmental (green) technology** is *the systematic knowledge of, and its application to production processes, making efficient use of natural resources while reducing/recycling wastes, to control/minimize the risks of chemical substances, and to reduce pollution* [18,27]. It includes cleaner production, supply chain management, waste minimization and zero waste.

5.1.2. Integrated pollution prevention and control

The EEA has defined **Integrated Pollution Prevention and Pollution Control (IPPC)** as *a legal process, by which large industrial processes are licensed and regulated*, referring specifically to the requirements of the European Commission's directive [1,28]. The main objective of the IPPC is to prevent or minimize emissions to all media as well as waste from industrial and agricultural edifications and their activities, whether new or existing, in order to achieve environmental protection. These obligations cover a list of measures following discharges into water, air and soil, and following waste, wastage of water and energy, and environmental accidents [29].

5.1.3. Industrial ecology

There are several different definitions of **industrial ecology**. The best one has been proposed by UNEP: *Systems-oriented study of the physical, chemical, and biological interactions and interrelationships both within industrial systems and between industrial and natural ecological systems* [15]. The definition includes the system's theory, well-known in ecology.

Industrial ecology is closely related to industrial ecosystems. In ecology, an ecosystem consists of various complex environs and sub-systems. The most important issues are the interrelationships, because they present a basis for interconnections between environs. Therefore, the **industrial ecosystem** represents *a group of enterprises that utilize each other's materials and by-products such that waste materials are reduced to an absolute minimum* [23]. The consumption of energy, raw materials, water and other resources is optimized in an industrial ecosystem, and waste from one process serves as a raw material for another.

Industrial ecology has influenced the development of **eco-industrial parks**. It is *a community of businesses, manufacturing and services, located together in a common property, seeking enhanced environmental, economic, and societal performance through collaboration in managing environmental and resource issues including information, energy, water, materials, infrastructure, and natural habitats* [15,23]. The benefit of such a community is greater than the sum of individual benefits [6]. This community benefits from the relationships and interconnectedness between environs and their environment.

Cradle to cradle is a paradigm, based on principles in which materials are viewed as 'nutrients' circulating in closed loops [30]. The term can be related to industrial ecology, because both terms are designed to mimic nature, where everything is used and nothing becomes a waste. This maximizes the material value without damaging ecosystems. On the other hand, cradle-to-grave assessment considers impacts at each stage of products' life cycle from the time when natural resources are extracted from the ground to their final disposal [1].

5.1.4. Pollution prevention

Although several definitions of pollution prevention are available, a similarity between them remains. Despite the EPA's definition of pollution prevention emphasizing the essential concept, new definitions are still emerging. The most common explanation discussing indirect semantic relationships and representing a consistent and reasonable definition was introduced by the Centre for Environmental Training and International Consulting (CENTRIC) [17]. This definition has its roots in the U.S. EPA's definition, **pollution prevention** being *a multi-media environmental management approach which emphasizes the elimination and/or reduction of waste at the source of generation*. In our opinion, the more appropriate term is 'strategy' instead of 'approach', because the term encompasses numerous principles and approaches.

The need to investigate all types of waste in order to protect the environment and conserve natural resources has spurred implementation of the pollution prevention strategy. The objective of the strategy is to stop the production of pollutants before they are generated and to achieve sustainable improvements, involving not only conservation of natural resources and materials, but also preventing accidental spills and releases, and avoiding exposure to toxic and dangerous materials.

An ambiguity was recognized between the terms 'cleaner production' and 'pollution prevention'. Cleaner production has a definition similar to pollution prevention; the term 'pollution prevention' is more frequently used in North America, and 'cleaner production' is used throughout the world.

Firstly, a lot of similarities have been recognized. Both definitions emphasize the pollution prevention principles, efficiency improvements through source reduction and beneficial use of resources and energy. Unlike the past when pollutants were simply controlled and treated, pollution prevention and cleaner production are both designed to prevent, reduce or eliminate pollutant production and transfer to all media in efficient and sustainable ways [17]. Both terms also involve cost reduction as their activities. Importantly, hazards to society and environment should be decreased at their sources. Moreover, cleaner production can be included in pollution prevention performance since it directs prevention-oriented activities within the industrial sector [24].

Nevertheless, differences between these two terms exist. Pollution prevention is established as a strategy. Semantically, a 'strategy' is obviously a broader term than an 'approach' (tactics), as introduced in the cleaner production definition. Moreover, pollution prevention differs from cleaner production in the fact that it comprises services and, therefore, encourages continuous performance of all activities, i.e. environmental management. Therefore, pollution prevention is an approach that is not only manufacturing oriented but can be applied to other sectors and services in general, from households to the tourism. In practice, cleaner production is applied also to services, from household, corporate and financial sector to tourism and others, but from a semantic point of view it is incorrect. Therefore, we have proposed a new definition for cleaner production.

5.2. Economic and societal strategies

Societal and economic dimensions are introduced through Economic and Societal sub-systems: *Environmental Management System* (*ISO 14000, Eco-management and Audit Scheme (EMAS)*), and *Product Service System*. Such strategies provide better quality of life and harmony with the surrounding ecosystem. Although, in some of the terms, the word 'system' appears, they are a sub-system in our classification.

5.2.1. Environmental management strategies

Environmental Management Strategy (EMS) presents a sub-system created to manage the environmental performance of organizations. **EMS** is *a set of management tools and principles designed to guide the allocation of resources, assignment of responsibilities and ongoing evaluation of practices, procedures and processes, and environmental concerns that industries, companies, or government agencies need to integrate into their daily business or management practices* [31]. EMS ensures that environmental issues are systematically identified, controlled, and monitored. It provides a mechanism for responding to changing environmental conditions and requirements, reporting on environmental performance, and reinforcing continual improvement [32]. EMS also embraces Supply Chain Management.

The **ISO 14000** series is *a family of environmental management standards developed by the International Organization for Standardisation (ISO)*. The ISO 14000 standards are designed to provide an internationally recognized framework for environmental management, measurement, evaluation and auditing. They do not prescribe environmental performance targets, but instead provide organizations with the tools to assess and control the environmental impact of their activities, products or services. The standards address the following principles: environmental auditing, environmental labelling and declarations, environmental performance evaluation, as well as approaches: environmental management and life cycle assessment [1].

Eco-management and auditing scheme (EMAS) is *the European Union's (EU) voluntary instrument that acknowledges organizations, which improve their environmental performance on a continuous basis* [33]. EMAS was originally designed for enterprises within industrial/manufacturing sectors. In 2001 the Regulation of the European Parliament, proposed EMAS for all the organizations, having environmental impacts, including public ones [34]. Therefore, EMAS introduced the tool for all organizations (i.e. enterprises, institutions, public and private organizations) in the EU area, to better manage their environmental impacts and to contribute to a more sustainable future. The objective of the scheme is to promote continuous improvements in the environmental performance of industrial activities by: (a) the establishment and implementation of environmental policies, programmes and management systems by companies, in relation to their sites; (b) the systematic, objective and periodic evaluation of the performance of such elements; (c) the provision of environmental performance information to the public [1]. Therefore, EMAS fosters organizations to estimate and improve the environmental efficiency, and publish their environmental achievements. On the other hand, EMAS presents a management strategy for companies and other organizations, evaluating, reporting, and improving their environmental performance.

5.2.2. Product service systems strategy

The term **product service systems (PSSs)** have been defined as *a marketable set of products and services capable of jointly fulfilling a user's need. The product/service ratio in this set can vary, either in terms of function fulfilment or economic value* [35]. Thus, more traditional, material-intensive ways of product utilization are replaced by the possibility of fulfilling consumers' needs through the provision of more dematerialized services, which are often also associated with changes in ownership structure [36]. The importance of product service systems ought to be in satisfying equity and the requirements of people with low budgets.

6. Sustainable systems

A system is a group of interdependent and interrelated subsystems comprising a coherent entity. Sub-systems function together as a whole to accomplish sustainable development.

Sustainable systems present the highest level of activities required in order to make progress towards sustainable development. The achievement of such objectives demands a change in thinking patterns, and lifestyles. The term 'sustainable systems' incorporates *Responsible care*, *Sustainable consumption*, and *Sustainable production*.

6.1. Responsible care

Responsible care is *the chemical industry's global voluntary performance guidance system, which shares a common commitment to advancing the safe and secure management of chemical products and processes*. '*Responsible care*' practices may vary between countries and each country's law does not determine them. Therefore, '*Responsible care*' enables companies to go above and beyond government requirements and the companies must openly communicate their results to the public. It encompasses employees, transportation and process safety, releases into the environment, distribution incidents, eco-efficiency, etc. [37]. The term includes environmental management systems as well as product service systems.

Practices of making health, safety and environmental improvements an integral part of sustainable systems can importantly contribute to more sustainable societies.

6.2. Sustainable production

Sustainable production is *creating goods by using processes and systems that are non-polluting, that conserve energy and natural resources in economically viable, safe and healthy ways for employees, communities, and consumers and which are socially and creatively rewarding for all stakeholders for the short- and long-term future* [38]. The term encompasses pollution prevention, IPPC, environmental engineering and technology.

6.3. Sustainable consumption

Sustainable consumption is *about finding workable solutions to social and environmental imbalances through more responsible behaviour by everyone*. In particular, sustainable consumption is linked to production and distribution, use and disposal of products and services, and provides the means to rethink personal life cycles. The aim is to ensure that the basic needs of the entire global community are met, excess consumption of materials and energy is reduced and environmental damage is avoided or reduced [39]. The term embraces industrial ecology and product service systems.

7. Sustainability policy

Sustainability policy is *a set of ideas or a plan of what to do in particular situations that has been agreed officially by a group of people, a business organization, a government or a political party* [20], *about environmental, economic and social issues*. Sustainable policy is important on institutional, corporate, as well as on regional, state, and alliance level. Therefore, we added sustainability policy as a fourth dimension. Policy can be locally, nationally or internationally oriented and can address issues such as sustainable development, climate change, air, water, waste, health, etc. For example, the European Commission proposed Declaration on Guiding Principles for Sustainable Development [46]. The term policy is closely related to environmental legislation.

There exist many international documents, frameworks and declarations, designed to foster sustainable development at all levels and to help society to make progress toward sustainable development. The Agenda 21 and the Rio Declaration on Environment and Development were adopted by more than 178 Governments at the United Nations Conference on Environment and Development (UNCED) held in Rio de Janerio in 1992. Agenda 21 is a comprehensive plan of action to be taken globally, nationally and locally by organizations of the United Nations System, governments, and major groups in every area in which humans have impact upon the environment [40], while The *Melbourne Principles* present a vision of sustainable cities, and have been developed to assist cities to achieve sustainable development. The *Melbourne Principles* provide a simple set of statements on how a sustainable city should function [41].

Some globally oriented documents include: *The Earth Charter, The Natural Step Principles*, and *UN Millennium Development Goals (MDGs)*. The Earth Charter is a declaration of fundamental principles for building a just, sustainable, and peaceful global society for the 21st century [42]. *The Natural Step Principles* are four principles, necessary for survival of the ecosystems, and refer to the society and its environmental impact [43]. *The Earth Charter* and *The Natural Step Principles* present a bottom up approach, fostering global policy, while the MDGs, including environmental sustainability, where the target is also to integrate the principles of sustainable development into country policies and programmes that include a top-down approach [44].

8. Sustainable development

Sustainable development could be introduced as a *process or evolution.* Numerous definitions of sustainable development are attainable but, in principle, they remain similar to the one from 1987. In that year the World Commission on Environment and Development (i.e. Brundtland's Commission) defined sustainable development as *''…development that meets the needs of the present without compromising the ability of future generations to meet their own needs''* [45].

Sustainable development emphasizes the evolution of human society from the responsible economic point of view, in accordance with environmental and natural processes. Therefore, the political dimensions are central elements. Furthermore, in a sustainable development paradigm the limitations of economic, societal and environmental resources are considered in order to contribute to present and future generations' welfare and can be applied on local, regional, national and international levels, based on political will.

9. Classification and relationships of terms

Classification means allocation of a term in comparison with other terms, according to their essential characteristics. The most important characteristics are the semantic meaning, and the size of the term. These features build a basis for the determination of relationships among terms. We propose a hierarchical and interdependent concept, made of definition nodes. The conceptual graph allows better understanding of the terms (see Fig. 1).

The terms are organized according to their characteristics, introduced by principles that present the basic elements for building more complex (sub)systems. These categorizations are presented through triangular planes and the positions of the terms within the triangle depend on their orientation (economic, ecological, and societal). Another dimension, which has been added, is political, presenting a top of the pyramid. In our paper, causal relationships between the terms have been pointed out. For example, the *eco-design* approach is including *eco-efficiency, health and safety, reuse, remanufacturing, and recycling*. On the other hand, eco-design presents a component of more complex sub-systems; therefore, it was included in the definitions of *environmental technology*, *environmental engineering*, and *pollution prevention*. Similarly, pollution prevention, and environmental technology/engineering are parts of *Sustainable Production* as a sustainable system. Policy is the fourth dimension, presenting political will of countries besides the environmental, economic and societal issues. *Sustainable development* is a timeline, where principles, approaches, strategies and policies may help us to develop and implement our future vision of a sustainable society that will require different thinking patterns and changes in lifestyles to achieve. System's approaches can help us to manage our societies in a more thoughtful and preventively oriented manner that can result in improved and hopefully more humane societies.

10. Conclusions

Sustainability terms, their definitions and interconnections are crucial for understanding and for better communication in the process of moving our societies toward sustainable development. To help to achieve this, the authors of this paper sought to clarify the meanings and applications of 51 terms and their definitions. Particular emphasis has been given to the environmental engineering field. Some improved definitions are proposed and argued. Furthermore, the relationships among terms, based on semantic similarities and differences, have been established. Each term has its own definition and semantic features, but it is difficult to isolate it from the other terms. All the terms form an interconnected system. Also, sustainable systems introduce interconnections between environmental protection, economic performance and societal welfare, guided by a political will, and ethical and ecological imperatives. Therefore, it is of utmost importance to understand the relationships among the terms, and their semantic meanings.

The authors hope that the discussions in this paper will assist the scientific community, policy makers and other stakeholders to better understand sustainable development issues and to avoid imprecise usage of the terms. Clearly, additional studies are needed to enhance further development and to establish a database for sustainability terms and their relationships that can further help societies to make progress toward more sustainable patterns.

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Assessment of environmental sustainability integration into higher education for future experts and leaders

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ABSTRACT

The environmental and climate crisis is gaining priority among critical human concerns; therefore, environmental knowledge and sustainable solutions play a significant role and gaining global popularity as an academic discipline. Additionally, United Nations Sustainable Development Goal no. 4 acknowledges education's role in promoting sustainable development, sustainable lifestyles, human rights, social responsibility, circular economy, and greening our economy and society. In this paper new conceptual framework that focuses on systematically analyzing environmental sustainability integration in study programs and subjects is developed. The main aim is to reflect the conceptual basis of education related to environmental sustainability topics such as sustainable development, social responsibility, circular economy, ecology, environmental protection, and greening to boost future environmental management practices in industry and services. Defining the level of integration of environmental and sustainability-related topics is divided by research field classification and study cycles (BSc, MSc, PhD). The specific added value of the developed conceptual framework is reflected by defining cross-sections and inter-and trans-disciplinary of sustainability topics integrated within specific programs and subjects. The conceptual framework was tested by assessing 1051 programs in progress in Slovenia. It was revealed that the highest share of study programs has an intermediate level of environmental sustainability with 2–3 subjects (392 study programs). These are represented mainly by integrating environmental protection, ecology, and "greening" but less with circular economy and social responsibility. Significant differences among specific study programs and study fields reflect that young intellectuals will not be equally educated and qualified for future managerial challenges. Master students gain the best insight into core sustainability and environmental topics needed for future environmental managers.

Author credit statement

Matevž Obrecht: Conceptualization, Methodology, Validation, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition, Zane Feodorova: Data curation, Writing – original draft, Visualization, Maja Rosi: Validation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing.

1. Introduction

In recent years, sustainable development and climate crisis are becoming the top humans' concerns; therefore, environmental knowledge and education on sustainable solutions play a notable role even though these issues are gaining complexity. Environmental knowledge involves human dissubject about interrelationships with the environment and can help improve environmental behavior (Zareie and Navimipour, 2016) and people's health and productivity.

When focusing on becoming sustainable, educating human resources (especially management) on sustainable development, environmental sustainability, and various environmental protection concepts should be carried out, especially in higher education (Daneshjoo et al., 2020). The doctrine of sustainability science is widely acknowledged as a tool for attaining global sustainability and is becoming the core philosophy of national and international developmental agendas also as a part of the United Nations Sustainable Development Goals (SDGs) that acknowledges the role education plays in the promulgation of Sustainable Development (SD) by acting as a thread that concatenates the other

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SDGs (United Nations, 2015). Hence, it is gaining global popularity as an academic discipline (Piza et al., 2018) and core competency for managing sustainability and Environmental, Social, and Corporate Governance (ESG).

Higher education for sustainable development addresses ill-defined, highly-complex real-world problems, such as climate change, pollution of environmental media, exhaustion of resources, overproduction of phosphorus and nitrogen, biodiversity loss, unjust distribution of wealth, circular and sharing economy, and degrowth. Sustainability in higher education is a prolific field of study (Viegas et al., 2016). In general, there is a broad understanding that higher education plays a crucial role in transforming studies and society towards a more sustainable development paradigm (Barth and Michelsen, 2013), with efforts to integrate sustainability into the curriculum (Benton-Short and Merrigan, 2016). Ayalon and Avnimelech (2007) believe that investing in environmental education at the university level can lead to a more environmental-friendly leadership in the future since most of the future generation of leaders, engineers, economists, and educators go through the university education system. Thus, higher education for sustainable development needs to be transformative (Brudermann et al., 2019) in challenging worldviews, assumptions, and values we as a society hold (Howlett et al., 2016).

The topic has gained importance in recent years, and the steep increase can be seen in the number of related publications. The reviewed studies (Brudermann et al., 2019; Daneshjoo et al., 2020; Daub et al., 2020; Do, 2020; Eppinga et al., 2020; Glavič, 2006; Vagnoni and Cavicchi, 2015; Valderrama-Hernández et al., 2019) are more or less concise – lack of environmental and sustainability education and development of new innovative frameworks to improve it can be seen all over the world.

This paper conducted an in-depth analysis of 1051 study in progress in Slovenian public and private HEI programs divided by study fields and study cycles based on a novel conceptual framework focused on assessing the content and interdisciplinarity of sustainability topics within study programs and subjects within them. Our primary research questions were a) how well is environmental sustainability included in HEI, b) what are the priority topics taught, and c) what are their intersections and overlapping. Therefore, the conceptual framework was divided into two stages a) study programs and b) specific topics taught within subjects included. The conceptual model developed presents a novel theoretical approach that is the only one that enables assessment of overlapping and interdisciplinary among study programs and specific subjects with a goal to define the supply of knowledge available and transferred it to future managers and environmental experts within existing HEI. Therefore this paper contributes to institutional theory by studying inconsistence from different perspectives (normative, legislative, strategic priorities) supported by cross-sections of priority topics taught and is targeting at altering beliefs, behaviors, and ultimately HEI performance supported by the developed conceptual framework.

Reviewing and assessing the national higher education system regarding its integration of environmental sustainability is an emerging need of every country (Álvarez-López and Matarranz, 2019) focused on achieving SDG. Therefore, the novel approach used in this research could be of international relevance since it enables assessment of the level and field of education most appropriate for future environmental managers and promotes new directions toward a sustainable society.

The following section investigates the literature review, and the investigated higher education system specifics. Further results are divided into integrating environmental sustainability topics among study levels and study fields within a) programs and b) specific subjects, and c) analyzing and interpreting key topics integrated and their cross-sections. The discussion gives new insight into inter-and trans-disciplinary sustainability elements interprets study approach applications and directions for future environmental experts' education.

2. Review of related research

Studies mainly perform just a brief review of study programs according to the specific field of education (Boarin et al., 2020) or are focused on one institution only (Brudermann et al., 2019). Specific approaches to integrating sustainability into higher education institutions' structures and processes were also studied (Daub et al., 2020) but not examined comprehensively enough regarding curricula analysis. Some of them focus on learner-centered and action-oriented approaches to educate future generations (Fokdal et al., 2020) and elaborate on the topic using case studies (Wamsler, 2020) or are focused on different university rankings (Glavič, 2006; Kovačič Lukman et al., 2021).

Some focus only on public but not private HEI; Eppinga et al. (2020) analyzed state universities in the Caribbean, then Vagnoni and Cavicchi (2015) investigated Italian public universities. Other assessed programs by experts instead of a real investigation of curricula with an in-depth analysis of actual subject content (Ulmer and Wydra, 2020). Sustainability perception was identified as well investigated by Bell et al. (2020), Valderrama-Hernández et al. (2019), focusing on students' vision of sustainability education and related to developing effective pedagogy (Sandri, 2020). Despite that, study programs and subject content/topic analysis are lacking.

The number of subjects and priority topics taught should be extensively studied to develop curricula that enable sustainability-oriented education of future managers, experts, and other social stakeholders and their environmental awareness (Kopnina, 2020). According to Wamsler (2020), more integral approaches and pedagogies are urgently needed; however, the current situation needs to be investigated first. The increasing importance of sustainability education is also visible in changing university degree catalogs to make sustainability focus more visible for students and their future employers, as sustainability is becoming one of the core challenges for future managers (Zorio-Grima, 2020).

One of the first studies investigating sustainability education at universities was the study of Glavič (2006), who observed the evolution of subjects from an end-of-pipe approach to pollution prevention to sustainability-related subjects. The topic was also investigated from the perspective of elementary schools' ecological pattern of education for SD and designing a new teaching model for increasing SD integration (Daneshjoo et al., 2020). Brudermann et al. (2019) wanted to reflect the conceptual basis of education for sustainable development in Austria, where the first respective study programs were established approximately 20 years ago. A survey among students in sustainable development and related fields contrasts their views and expectations within the elements of sustainability education since they demand more knowledge on sustainability-related topics and environmental management (Obrecht et al., 2021). However, research relations of education for SDG done by Kopnina (2020) showed that despite the willingness of many educational institutions worldwide to embrace the SDGs, whether SDG no. 4 is desirable as a future education for all remains.

Boarin et al. (2020) found out that nearly all students generally consider sustainability a crucial part of their education. No matter that, high variations among study programs with different goals and design focuses can be identified. No matter that, Paço and Lavrador (2017) found out that there is a lack of relationship between environmental knowledge and attitudes and between environmental knowledge and environmentally friendly behaviors among students. Sustainability needs to be integrated into subjects, such as marketing, which do not currently promote sustainability for better environmental sustainability education. It also has to be supported by new (social) media. Contrary, the marketing disciplines usually promote consumption and advocate material accumulation as an indicator of success, no matter that numerous studies revealed that this does not make individuals happy (Kemper et al., 2020). Sustainability science as a standalone subject is yet to gain prominence in educational systems, even though certain scientific principles and practices have been included within existing subjects like environmental sciences. Priyadarshini and Abhilash (2020) found that none offered sustainability science, but half offered environmental sciences in India.

Research on sustainability education has neglected to integrate entrepreneurial skills into relevant competencies such as foresight, complex problem-solving, and interdisciplinarity (Hermann and Bossle, 2020). Almost 60% of all environmental impacts are caused by small and medium-sized companies (SMEs), where entrepreneurs/managers often do not have special knowledge related to environmental sustainability and no special empowerment for managing it (Denac et al., 2018). Since sustainability is gaining importance, it is recommended that sustainability education be more incorporated into business studies (Hay and Eagle, 2020) and lifelong learning. According to Mulder (2017), implying 'sustainable development' issues and learning about them should be the leading principle also for organizing an engineering curriculum. Some research related to sustainability education also focuses on the sustainability performance of student campuses (Ozdemir et al., 2020) or the institutionalization of sustainability into an organization's structure (Roos and Guenther, 2020). Both ideas can impact students' sustainable education and performance and HEI staff.

Analyzing the context, the role of education, gaps in existing and required competencies, and sustainability performance was earlier exposed by Orlović-Lovren (2011) and Wang et al. (2013), mentioning that the transformation towards an ecologically sound society needs adequate education programs.

3. Methods

The conceptual framework was developed by summarizing eight steps of the Jabareen methodology (Jabareen, 2009) into three steps: collecting the data (including mapping the data sources and extensively reading and categorizing the selected data), building the conceptual framework, and testing the results. The data for creating the conceptual framework comprises different scientific literature. The conceptual framework for assessing the content and interdisciplinarity of sustainability was developed and is divided into two stages a) on study programs and b) specific topics taught within subjects included. The conceptual framework enables assessing the interdisciplinary and topic overlapping among study programs and specific subjects. This conceptual framework (presented in Fig. 1) provides a comprehensive understanding of HEI sustainability education. Testing was done by comprehensive analysis of a selected HEI in the EU Member State since sustainable development is prioritized within the EU strategic goals. Study programs were identified, and the content/curricula of each subject within these programs were thoroughly reviewed and assessed based on different criteria developed within a conceptual framework:

Stage 1a) Level of integration of sustainability and environmental topics on a scale from 1 (low) to 5 (strong integration) regarding the name, content as well as percentage and relevance of thought content related to SD and environmental issues in 1) study programs and 2) in subjects/curricula;
Stage 1 b) Analysis of study programs according to low (0–10% of subjects), medium (10–25% of all subjects), and high (25 or more subjects) integration of environmental and sustainability topics;
Stage 2) Topics are addressed by examining program curricula and subject content. Selected keywords for the analysis were: 1) "green/environmental"; 2) "environmental protection," 3) "ecology (-cal)"; 4) "sustainable development/sustainability," 5) "circular (economy)" and 6) "social responsibility" combined with related acronyms and synonyms;
Stage 3) Defining current topic priorities and analyzing their inter- and cross-sections to define which topics are well interconnected and still lack stronger relations.

This conceptual framework was tested on 1051 study programs valid and in progress in the Slovenian higher education system based on 57 public and 49 private HEIs, and insights represent this study's focus.

Analysis was made for all three study degrees (bachelor, master, and doctoral) and was investigated separately for 9 study fields classified by KLASIUS-P (1. Educational science and educating teachers (professors); 2. Art and humanities; 3. Social, business, management, and law studies; 4. Natural science, mathematics, and computer engineering; 5. Technics, production technologies, and construction; 6. Agriculture, forestry, fishery, veterinary studies; 7. Health and social care, 8. Services and 9. Unclassified). Data were collected for public universities and faculties, applied science universities, and private faculties. Class "Unclassified" (KLASIUS-P no. 9) was excluded from the survey since no study program was defined as a class no. 9 – "unclassified."

Results were statistically processed to define low (1–2 subjects, which typically represents 0–10% of all subjects), medium (3–6 subjects which typically represents 10–25% of all subjects), and high (7 or more subjects, which typically represents at least 25% of all subjects) integration of environmental sustainability in available study programs. SPSS software was used to perform the statistical analysis.

Analysis was also performed to define nine areas according to the national KLASIUS-P classification and their integration of environmental sustainability. To determine the level of inclusion of environmental sustainability topics in specific subjects within study programs Likert scale (from 1 to 5) was used. On this scale, 1 means WEAK

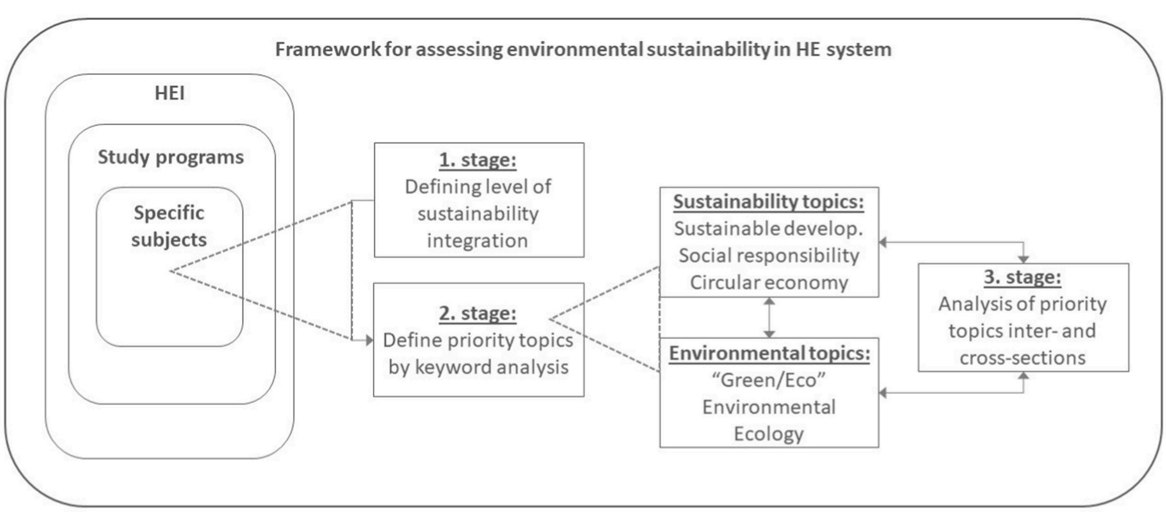

Fig. 1. Conceptual framework for in-depth assessment of sustainability integration in HEI.

integration (e.g., only a few words in the curriculum related to environmental sustainability), 2 LOW, 3 MEDIUM integration (e.g., one third to half of the topics are dedicated to the topics of sustainable development), 4 HIGH and 5 STRONG involvement (the subject is mostly or entirely devoted to the topic of sustainable development and environmental protection). Results were aggregated in some cases to be presented on three intervals, same as in other sections, where 1 means LOW (aggregated by 1 weak and 2 low), 2 MEDIUM (3 Medium), and 3 HIGH (4 High and 5 Strong) integration. Integration of environmental and sustainability topics within subjects that included sustainability/environmental synonyms in the subject name was also compared to those that did not have sustainability/environmental synonyms in the subject name. The main focus of this analysis was to investigate whether those subjects with the name clearly showing the focus on environmental and sustainability topics are offering more content related to sustainability and environmentalism compared to other subjects and see to what extent and to evaluate further priority topics taught.

4. Results

Testing developed conceptual framework proved to give detailed insights on a) integration of sustainability and environmental topics, b) keywords addressed, c) analysis of sustainability integration into study programs and specific subjects, and d), most notably, defining priority topics and their cross- and inter-sections in selected higher education system of Slovenia.

4.1. General findings on environmental and sustainability integration

90.5% of investigated study programs offer at least one subject integrating environmental or sustainability-related topics. 61.4% are regular, and 38.6% are elective subjects. Fig. 2 indicates that most study programs (36% of all programs in Slovenia) are focused on natural sciences, mathematics, and computer sciences, with the highest number of PhD programs (65% of all PhD programs in Slovenia) as well as Master programs (46% of all Master programs).

The lowest share of study programs is found to be integrated into arts and humanities (1% of all Slovenian study programs). Most bachelor-level study programs (Professional – 22% and University – 30%) are in the engineering, manufacturing, technologies, and construction classification group.

Both public and private HEIs are more oriented towards environmental topics, with slight domination of environmental and sustainability programs and subjects in public (80.9% environmental and 47.1% of sustainability topics) HEIs. Private has slightly lower integration with a share of 75.7% of environmental and 43.8% offering sustainability topics (see Table 1).

According to the developed framework, the level of integration (low, medium, and high) of environmental sustainability topics into specific study programs was classified into three groups. If it consists of one to two subjects in the study program, the study program was identified to have a LOW level of integration in the faculty, three to six subjects MEDIUM level of integration, and seven or more subjects per study program to have HIGH integration of environmental sustainability topics.

First, we examined the integration of sustainability topics in the subject name (see Table 2). 1–2 subjects containing sustainability education-related keywords in titles were identified in ten study programs. Eleven study programs were determined to have 3–6 subjects, and 41 study programs could offer more than seven subjects (combining regular + elective) per study program. The curriculum included 11 subjects with the keyword “environmental/green” with a low level of involvement, a medium level of involvement, 12 study programs, and 41 study programs with a strong inclusion. For the keyword “sustainable/sustainability,” 12 study programs were evaluated at a low level in the curriculum, 9 study programs were evaluated with medium inclusion, and 36 study programs with strong integration. It can therefore be seen that environmental topics outperformed sustainability topics.

Below in Fig. 3, the difference among subjects with environmental/sustainability included in the subject name and other subjects is presented. As predicted, subjects with environmental and/or sustainability included already in the name have a much higher integration of environmental and/or sustainability content than the rest.

Table 1
Share of study programs with subjects related to environmental and sustainability topics in public and private HEIs.

Type of institution		Environmental topic		Sustainability topic	
		N	%	N	%
PUBLIC	NO	147	19.1	408	52.9
	YES	624	80.9	363	47.1
	Total	771	100.0	771	100.0
PRIVATE	NO	45	24.3	104	56.2
	YES	140	75.7	81	43.8
	Total	185	100.0	185	100.0

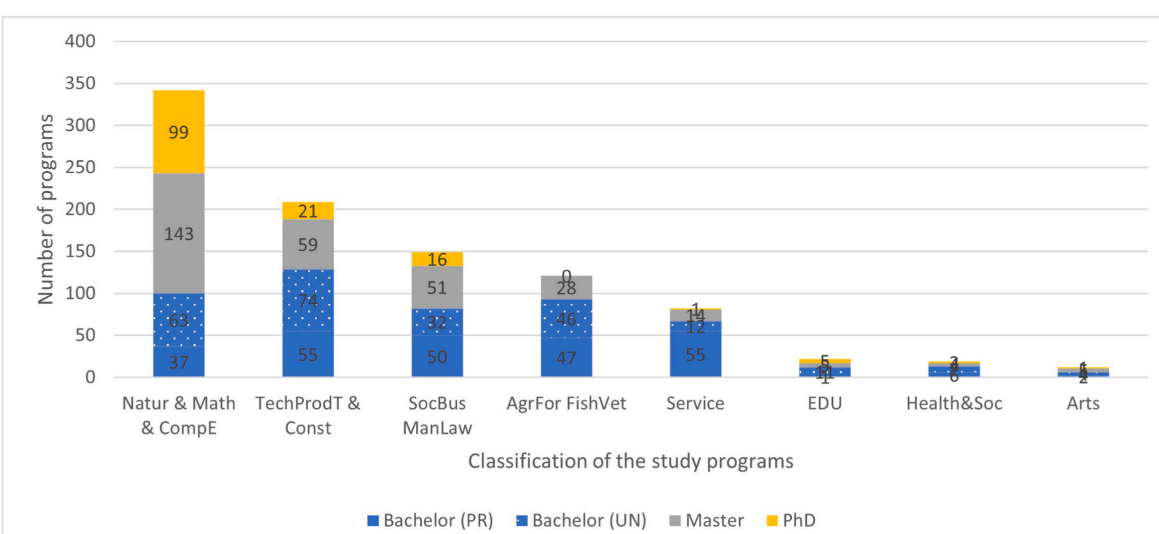

Fig. 2. Number of study programs per study level and classification.

Table 2
Integration of environmental sustainability topics in study programs by KLASIUS-P classification.

SUM (one of six keywords in the subject name)									
Study field (KLASIUS-P)	**1 EDU**	**2 Arts**	**3 SocBusManLaw**	**4 Natur&Math&Comp**	**5 TechProdT&Const**	**6 AgrForFishVet**	**7 Halth&Soc**	**8 Service**	**SUM**
Integration by subjects	10	6	76	225	122	51	14	46	539
Level of integration by HEIs	1-2 subjects	10	3-6 subjects	11	7 or more subjects	41			
"Environmental" related topics in the subject name									
Study field (KLASIUS-P)	**1 EDU**	**2 Arts**	**3 SocBusManLaw**	**4 Natur&Math&Comp**	**5 TechProdT&Const**	**6 AgrForFishVet**	**7 Halth&Soc**	**8 Service**	**SUM**
Integration by subjects	22	2	49	264	14	13	6	15	763
Level of integration by HEIs	1-2 subjects	11	3-6 subjects	12	7 or more subjects	41			
"Sustainability" related topics in the subject name									
Study field (KLASIUS-P)	**1 EDU**	**2 Arts**	**3 SocBusManLaw**	**4 Natur&Math&Comp**	**5 TechProdT&Const**	**6 AgrForFishVet**	**7 Halth&Soc**	**8 Service**	**SUM**
Integration by subjects	8	8	99	112	140	34	1	42	443
Level of integration by HEIs	1-2 subjects	12	3-6 subjects	9	7 or more subjects	36			

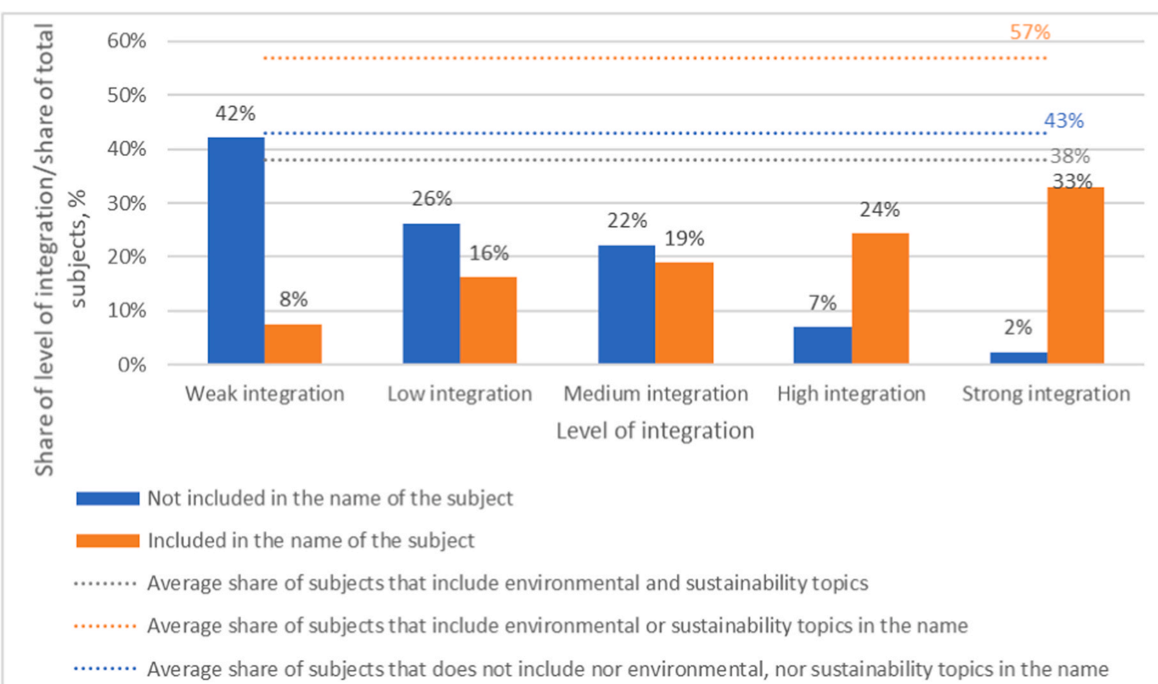

Fig. 3. Level of integration of environmental and sustainability topics regarding subjects name related to sustainability/environmental topics or not.

The average inclusion of environmental and sustainability topics in all study subjects is 38% (57% include environmental and 43% sustainable topics). Fig. 3 indicates that two blocks of inclusion exist. If keywords “sustainability” and “environment” are included in the subject’s name, the subject’s content will be firmly focused on the mentioned topics. A similar tendency can be observed the other way around. If keywords are not included in the name of the subject, low integration of environmental and sustainability content was detected. The highest share of Slovenian HEI study subjects (42% of all subjects) indicates weak integration of sustainability and environmental topics.

On the other hand, the second-largest share (33%) represents study subjects with strong integration of environmental and sustainability topics. Therefore, a divide among integration of sustainability and environmental-related topics could be misleading for non-professionals that interpret these data based on unsystematic analysis. Professionals responsible for environmental (and sustainability) management need education based on medium or strong integration. Naturally, some subjects were observed that do not include sustainability/environmental in the name but still have medium or strong integration in the subject’s content (7% fairly and 2% strong integration in the content).

The distribution of integration is significantly different when analyzing general data, as presented in Fig. 4. The highest proportion of Slovenian study programs indicates weak (considering weak and low) integration. Medium integration can be observed in 20.3% of Slovenian HEI, and high integration (considering the sum of Fair and Strong) is identified in 36.5% of programs.

4.2. Detailed program and subject analysis of environmental and sustainability integration

The environmental and sustainable topics inclusion revealed that most subjects have medium integration (392) followed by HIGH integration (350).

When comparing the integration of environmental vs. sustainability topics (and a combination of both), results indicated in Fig. 5a revealed that some study fields are much more related to environmental topics and much less to sustainability (e.g., EDU or AgrForFishVet). On the other hand, all EDU study programs have integrated environmental topics into their study programs, meaning that at least one subject is related to environmental topics. This high number could be explained by a relatively small number of EDU programs (22 or 2.3% of all HEI programs) that could all include the same environmental subject. The lowest results on environmental (32%) and sustainability (5%) topics inclusion indicate Health&Soc group which also lacks subjects including both topics combined. On the other hand, sustainability is highly integrated (68%) in TechProdT&Const, Arts, and SocBusManLaw, which also have most programs including both environmental and sustainability topics.

After gaining insight into environmental and sustainability topics in different study fields, which can be crucial information for employing environmental experts and managers, the study focused on analyzing the integration of environmental sustainability among the 1st, 2nd and 3rd study levels. As presented in Table 3, data show that 2nd level (Master’s degree) programs are best related to sustainable education, as 138 subjects have MEDIUM integration and 127 subjects HIGH/STRONG integration.

3 level (PhD) studies have minor subjects and relatively low average integration. No matter that, it should be noted that there are fewer programs and subjects at the doctoral level than at other levels of study. The syllabus is primarily elective and highly individualized. As visualized in Figs. 5b and 88% of all PhD programs have integrated environmental topics to some degree in the name of the study program. It is the highest share of any level program represented in the study. The figure indicates that sustainability topics are included noticeably less than environmental ones. The weakest integration of sustainability topic is noticeable for PhD programs, where only 39% has integrated sustainability topics. On the other hand, the best results for sustainability integration are revealed in Master level programs, where more than half of programs (54%) have integrated sustainability topics. When analyzing the integration of both topics, all study levels have a similar share (37–39%) of integration.

The joint analysis data showed that among all investigated HEIs, the Biotechnical field best integrates environmental sustainability topics. It proved itself with as many as 52 study programs and 237 subjects and consequently stood out in the environmental and sustainability field.

Detailed analysis of faculties and study programs with different environmental sustainability-oriented subjects divided them into three levels. 1st level included study programs with less than 10% of programs related to environmental sustainability (LOW), 2nd level those with 10–25% of all programs (MEDIUM), and 3rd level included those with 25% or more programs (HIGH) related with environmental sustainability. When reviewing study programs by faculties (departments), it was revealed that 14 faculties had high integration of environmental sustainability. Most HEIs offer 1-2 study programs (32 HEIs) related to sustainability and environmental protection, meaning that they provide low integration of environmental sustainability integration. 28 HEIs offer medium (typically 3–6 programs) integration.

Most programs contain 1-2 subjects related to environmental sustainability topics (111), followed by programs with 10–25% of subjects related to environmental sustainability. Only 35 study programs showed a strong focus on environmental sustainability, with at least 25% (typically seven or more) integrated regular or elective.

4.3. Specification and cross-sections of environmental and sustainability topics

Specification of environmental and sustainability topics was carried out to get a thorough insight into HEI programs and content. It revealed

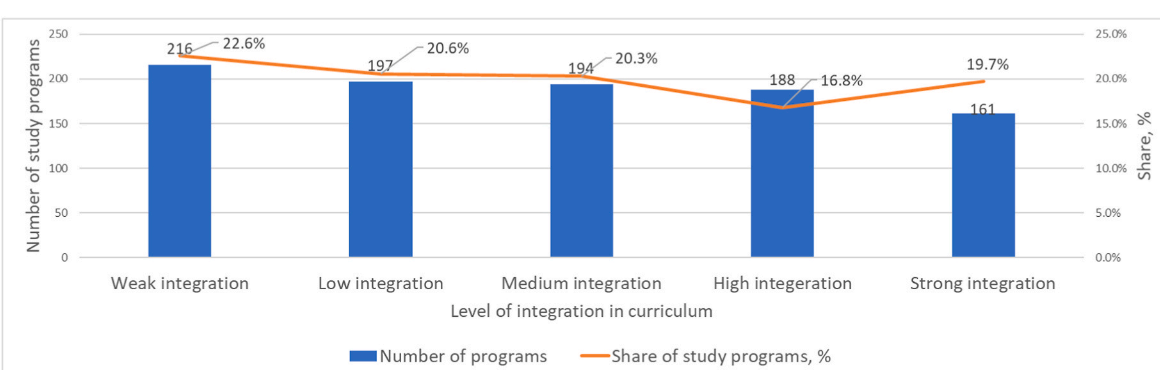

Fig. 4. Share of study programs, including sustainability and environmental aspects by the level of integration.

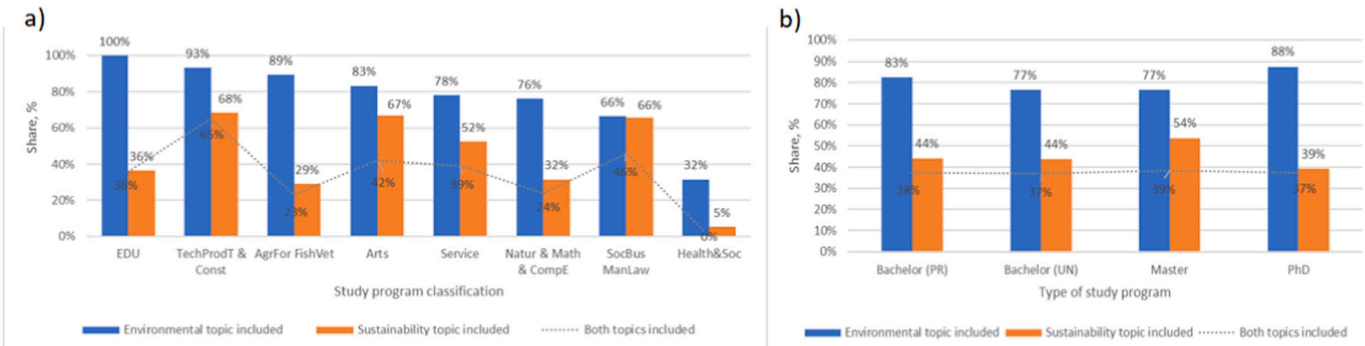

Fig. 5. a) Study fields divided programs including sustainability or/and environmental topics and b) Share of integrated sustainability and environmental topics among study levels.

Table 3
Integration of environmental sustainability topics by study levels (1st level – bachelor's University and Professional, 2nd level – master and 3rd level – doctoral studies).

Level of integration by study levels	LOW	MEDIUM	HIGH
1st level UN	74	91	83
1st level PR	58	106	85
2nd level Msc	42	138	127
3rd level PhD	31	57	55

that most included topics are: "environmental protection," "green/environmental and related acronyms," and "ecology." "Environmental" was most integrated with 522 subjects related to this topic. It is followed by "green/environmental and similar" with 487 subjects and "ecology/ecological," with 480 subjects mentioning this aspect in the curricula.

Education should include study topics on interdisciplinarity and various environmental and sustainability top for future competitive environmental experts. Therefore insight into intersections and combinations of multiple topics was carried out as the most important output of this research. It was revealed that most intersections were among 1) 'environmental' protection and 6) 'green/environmental' (305 intersections) and at the intersection of 1) 'environmental' protection and 2) 'ecology/ecological' (293 intersections). The third most common intersection was a combination of 6) 'green/environmental' and 2) 'ecology/ecological,' both mentioned in 230-subject curricula. All three topics were included in 164 cases, meaning that these programs should be on the priority list of future environmental managers and sustainability experts, leading us to a more sustainable future. Intersections are presented in Fig. 6.

The topics that are less included (see Fig. 6a) are 4) "sustainable development" (432 matches), 5) "social responsibility" (358 matches), and 3) "circular economy" (258 matches).

The cross-sections show which three pairs are the least included in the curriculum. The least suitable combination is represented in the intersection of the 3) "circular economy" and 5) "social responsibility," as only 127 subjects mentioned both topics in their curricula, which on the other hand, represent top priorities, especially in the EU strategic development. The central intersection in Fig. 6 shows that 101 subjects included all three least designated topics in their curricula.

At the end of the analysis of the inclusion of topics/keywords in the curricula of reviewed 956 individual subjects, there is 32 subject that includes all six topics, which could be defined as oriented explicitly towards different perspectives of environmental and sustainability science. This analysis brings new insights into overlapping topics within subjects and programs and enables HEI to define its interdisciplinarity in the field of sustainability.

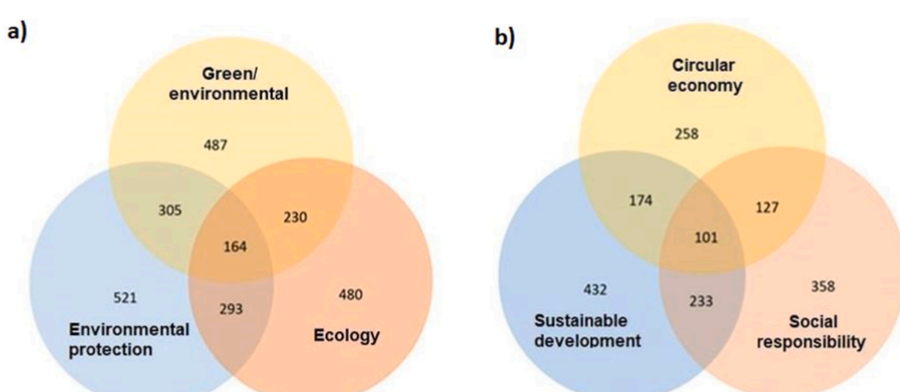

Fig. 6. a) Three most and b) three least (right side) frequent topics and their intersections among subject curricula (private and public HEIs).

5. Discussion and concluding remarks

Reviewing study programs and the subsequent analysis of the obtained data made it possible to detect considerable differences between study programs and specific HEIs. Those differences were noted among HEIs within the same University and even more among the different public or private HEIs in Slovenia. On the one hand, this result is logical, as the HEIs are primarily focused on specific areas of the economy; on the other hand, such diversity is challenging and requires better insight into the integration of particular topics for future graduates of specific fields. Most study programs (36%) related to environmental and sustainability topics are focused on natural sciences (NaturMathComp), with the highest number of PhD (65%) and Master programs (46%). The highest number of bachelor-level study programs (Professional – 22% and University – 30%) are in engineering (EngTechConstr). Results revealed that graduates of some HEIs or study programs could be much better acquainted with environmental sustainability than others, i.e., graduates of comparable programs and degrees of other HEIs and some study fields are more related to environmental topics and more minor to sustainability (e.g., EDU or AgrForFishVet). To form a comprehensive perspective on upcoming challenges of a sustainable society, HEIs should aim to offer a comprehensive combination of both disciplines that combines sustainability with environmental, social, and economic views.

When discussing the divide between private and public HEIs, it was clear that private HEIs offer slightly fewer subjects related to environmental and sustainability-related. Still, according to the results mentioned above, one of the reasons might also be that private HEIs are more focused on Social sciences and services and not that much on Natural sciences and Engineering, which are among the top performers in public HEIs.

Given the legislative framework and direction of six EU commission priorities also related to funding core research (e.g., Horizon Europe, 2021–2027), it is expected that environmental sustainability topics focused on the circular economy, sustainable development, alternative resources, smart and resilient society will be at the forefront of future HEIs curricula. In addition, considering their intersections and overlapping is about to bring new added value to future environmental managers' education. However, the structure of study programs reveals that HEIs are developing in the direction of EU strategic priorities, but their development might be more intensive. Therefore, the conceptual framework conceptualized and used in this paper is the only one that enables insights and assessment into inter-and cross-disciplinarities of sustainability topics and their overlappings within-subjects and programs. It is internationally applicable and could enable the assessment of priority topics in specific higher education systems and their compliance with national or international strategic priorities. The developed framework is based on flexible conceptual terms and might be reconceptualized and modified according to the evolution of sustainable education or new data and knowledge that is currently unavailable.

Interdisciplinary research and education are gaining importance. Whether information in a specific study program is oriented toward circular economy or social responsibility or these two topics, overlap and to which extent could gain significant importance in the future when there is a higher demand for competencies and knowledge related to specific environmental sustainability topics tied to specific segments of environmental management.

However, when examining study cycles, master's study programs include the highest share of sustainability, PhD highest environmental, and the lowest share of sustainability integrated topics. This phenomenon can be explained by the nature and the purpose of the program. Master graduates mostly take positions as managers, engineers, etc. (depending on the program). Still, PhD graduates are focused on a specific field with potential career development in research and academia. The environment might be integrated more than sustainability due to its topicality for the last ten years. On the other hand, sustainability only starts to rise to its glory. So the most beneficial level of education for environmental managers and professional experts is concluded to be MSc.

Nevertheless, higher education institutions play a significant role in sustainability provision, and by offering appropriate curricula, they can shape students' perceptions on those topics (Dagiliūtė et al., 2018). They also have a great potential to facilitate societal responses to the many sustainability challenges facing communities worldwide (Stephens et al., 2008) since they essential contribute to developing a sustainable and responsible society (Rosi et al., 2018).

It is also more than welcome to encourage interdisciplinary education based on study findings. Including different aspects of environmental protection and sustainable development into full-time study programs of all kinds could lead to integrating and tying at least one elective subject related to environmental sustainability to each study program. This kind of education would enable all interested students to deepen their knowledge in sustainability science no matter what their primary study focus is. Since creating new subjects and hiring sustainability experts might be expensive and irrational, especially for small HEIs, one solution is also proposed by implementing joint projects and elective subjects throughout diverse study programs that integrate sustainability into their curricula. This solution is also suitable for the HE system since it does not incur additional costs. To offer appropriate environmental sustainability knowledge to future generations, study program development should be done hand in hand with educating and building university staff awareness on those topics (Ralph and Stubbs, 2013). It was revealed by Mróz et al. (2018) that sustainable development promotion and teaching is not among teachers/professors' priorities and Eppinga et al. (2020) noted a lack of staff interest in improvements. Consequently, they might not be well prepared to promote and transfer such knowledge.

Higher education institutions have an important impact on training and preparing the future generation for a green society by providing appropriate environmental education to their students (Boca and Saraçlı, 2019). No matter where they will be working in the future, they need to become more aware of environmental and social challenges. To create sustainable and resilient business opportunities, a sustainable public sector, and transform society on the road towards a sustainable development paradigm, future experts have to learn how to address them first. To create authentic leaders who would guide society towards more sustainable ways of life (Chuvieco et al., 2018), comprehensive environmental and sustainability education should be integrated better into the HE curriculum.

Although the study was comprehensive, it was limited to descriptive statistics by limited public website data. Second, the results only reflect the Slovenian HE system, which could differ in other countries. The conceptual framework is also applicable in other local, national, or international environments.

Detailed analysis of the head of the universities, teachers' and students' perspectives, and environmental knowledge in different universities could add additional value to program and subject improvement and should be further investigated in future studies. Additionally, research potential is visible also by assessing the impact of environmental knowledge received from different universities on future careers. Especially if CEOs' decisions and organizations' contributions to sustainable development differ regarding the education acquired. Another aspect to investigate is also how national environmental policy could impact sustainability integration in HEI.

Declaration of competing interest

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

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