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Research

Unintended consequences of sustainable development initiatives: risks and opportunities in seagrass social-ecological systems

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ABSTRACT. Conserving biodiversity with a growing human population is a key sustainability challenge. Consequently, a vast number of development initiatives across the globe have been designed to combine social, economic, and environmental perspectives. For the most part, the development community is well acquainted with the negative experiences and unintended consequences that some projects have or may bring. However, in tropical coastal ecosystems, this aspect is not completely acknowledged, studied, or understood. Here, we use tropical seagrass meadows as a model social-ecological system to investigate how sustainable development initiatives result in unintended consequences with both positive and negative outcomes for environment and society. We analyze the initiatives and their effects in terms of a typology encompassing "flow", "addition", and "deletion" effects and investigate them across four types of sustainable development initiatives that occur within tropical coastal environments: (1) megafauna conservation, (2) alternative livelihood programs, (3) mosquito net malaria prophylaxis, and (4) marine protected areas. Using these four initiatives as examples, we show that sustainable development initiatives can produce unintended effects with major consequences. Further, we illustrate how not assessing such effects may ultimately undermine the initial goals of the sustainable development intervention. Our study suggests that acknowledging unintended effects and transitioning them so that they become sustainable is more effective than ignoring effects or viewing them as trade-offs. We strongly stress the need for an a priori process in which positive effects, negative effects, and potential uncertainties and surprises are considered when planning the development intervention, and we argue for greater social-ecological monitoring of initiatives. As such, this contribution links to contemporary approaches dealing with the sustainability of natural resources and social-ecological systems and bridges with the importance of development initiatives in the context of the United Nations Sustainable Development Goals.

Key Words: *seagrass meadows; social-ecological system (SES); sustainable development; systems change; unintended consequences*

INTRODUCTION

Human-driven degradation of nature is responsible for the biodiversity crisis (IPBES 2019), an issue simultaneously coupled with a climate emergency (Ripple et al. 2020) that has the potential to increase the risk of food-insecurity (Hasegawa et al. 2021) and poverty at global scales (Soergel et al. 2021). The 17 Sustainable Development Goals (SDGs; United Nations 2015) were conceived as a vision to ensure that humans and nature can thrive together (Mironenko et al. 2015), representing clear ambitions for societal development (e.g., SDG1 Zero Poverty, SDG3 Good Health and Well-being) and preserving nature (e.g., SDG14 Life Below Water, SDG15 Life on Land). Nongovernmental organizations (NGOs) are viewed as vehicles to implement sustainable development initiatives in the absence of strong, formal institutions (Brass 2016), so much so that since the release of the Brundtland Report (World Commission on Environment and Development 1987), the number of NGOs in low-income and emerging economies have exploded in number (Brass et al. 2018), size, and scope, ranging from large international NGOs such as Oxfam to smaller localized farmer associations (Banks et al. 2015). However, although the contribution of NGOs toward sustainable development is considerable (Lewis et al. 2020), challenges within the sector can impede progress (e.g., funding, focus on short-term results and short-term value for money; Banks et al. 2015).

Although analyses of SDG actions mostly suggest synergies between social and environmental targets, there are also indications of trade-offs (Nilsson et al. 2016, Pradhan et al. 2017). Trade-off analysis has grown steadily as a field of study, especially within terrestrial settings, but generally only concerns the known costs and benefits (e.g., Kanter et al. 2018, Scherer et al. 2018), i.e., outcomes that are planned for and anticipated. Thus, there is great need to understand and report the unknown or indirect costs and benefits, i.e., the unintended consequences, which can be numerous. In Zambia, for example, a community-based wildlife program driven by NGOs resulted in livelihood losses, food insecurity, malnutrition, and social conflicts for traditional communities for whom bushmeat was an important source of protein (Marks 2001). Moreover, Armsworth et al. (2006) noted that purchasing land for conservation initiatives could lead to greater biodiversity loss and more illegal land acquisitions if land market dynamics are ignored. Such unintended consequences are difficult to predict and design for (St John et al. 2013), but some can be anticipated and possibly avoided by considering different types of local and traditional knowledge and taking a multidisciplinary approach using both natural and social sciences (Minnes et al. 2020).

A social-ecological systems approach (Berkes and Folke 2000, Ostrom 2009) provides a conceptual framework for exploring the ways in which humans and nature interact (Carpenter and Folke 2006) and can be used to build resilience for sustainability (Olsson

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et al. 2004, Ostrom 2009). Such an approach can also be integrated into ecosystem-based management, which recognizes the need to incorporate systems approaches into natural resource management. Systems thinking can facilitate the understanding of coevolutionary dynamics and help interpret linkages between social and environmental change, and can also indicate how these linkages influence the achievement of sustainable development strategies (Berkes and Folke 2000, Fulton et al. 2011, Fischer et al. 2015). With the growing recognition that it is important to account for unintended consequences to better manage and implement sustainable development (Hull et al. 2015), integrating systems approaches into sustainable development planning could help to identify how systems cope with and adapt to change (Carpenter et al. 2009) and what traps and consequences occur in context-specific scenarios (Larrosa et al. 2016, Cumming 2018). Social-ecological systems perspectives have been used to investigate unintended consequences in agricultural (Zvoleff and An 2014, Steen-Adams et al. 2015), forested (Spies et al. 2014), and urban landscapes (Morzillo et al. 2014, Shandas 2015), and marine systems (Cinti et al. 2010, Davis et al. 2020). To our knowledge, examples are lacking for tropical coastal systems, even though these ecosystems support livelihoods and secure food for a large and rapidly growing proportion of citizens in tropical countries (Short et al. 2021).

Seagrass meadows are one such coastal ecosystem; they populate shallow coastal areas across most of the planet, including the tropics (McKenzie et al. 2020). These "underwater grasslands" remain marginalized in global policy, confounded by a lack of appreciation for the critical ecosystem services they deliver: food and livelihoods (Cullen-Unsworth et al. 2014), fisheries production (Unsworth et al. 2019*b*), carbon sequestration (Macreadie et al. 2014), human health support (Lamb et al. 2017), and culture (McKenzie et al. 2021), among others. Especially in the tropics, seagrass meadows support a plethora of services important for sustaining human life. They are often the primary habitat of choice for coastal fishers targeting both fish and invertebrates (de la Torre-Castro et al. 2014), reducing social vulnerability (Quiros et al. 2018). Food supply across the tropics depends on seagrass meadows (Unsworth et al. 2014), making them archetypical social-ecological systems. However, this concept has seldom been acknowledged within the seagrass scientific literature. Although some studies examine seagrass meadows as a social-ecological system (see de la Torre-Castro 2006, Nordlund et al. 2011, Cullen-Unsworth et al. 2014, Quiros et al. 2018), further understanding is necessary to support sustainable development that sustains and improves human well-being while conserving seagrass meadows in a changing world (Unsworth et al. 2019*b*). Most importantly, we need to understand the complex links and feedbacks that exist within seagrass social-ecological systems and whether these systems are resilient to change (Unsworth et al. 2015).

Here, we take an integrated approach to analyze a set of sustainable development initiatives from the perspective of seagrass social-ecological systems across the Indo-Pacific region, a bioregion with the world's highest seagrass diversity and largest seagrass distribution (Short et al. 2007). Using documented examples from the literature, we discuss sustainable development initiatives with effects that potentially result in unintended and often dire consequences for both people and nature. We argue that these consequences should be confronted and avoided or relieved to increase the likelihood of driving the systems into sustainable development pathways.

METHODS

Study region: Indo-Pacific ecosystems

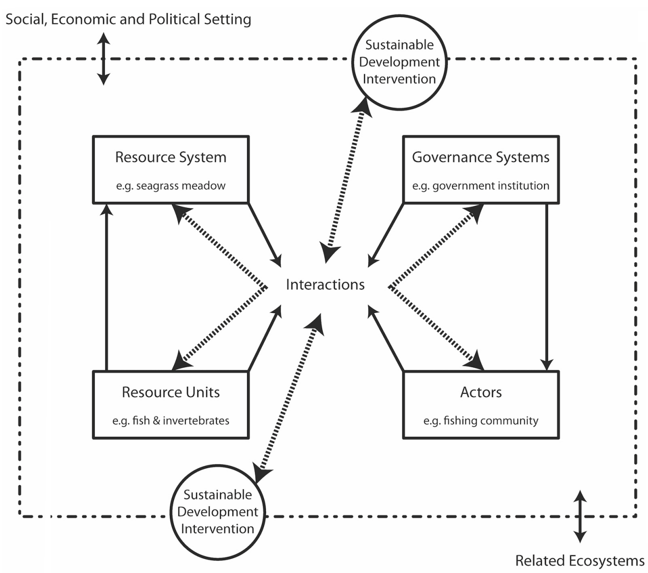
Of the six global seagrass bioregions, the Indo-Pacific hosts the highest seagrass species richness and largest seagrass distribution (Short et al. 2007) and is the most diverse in terms of associated seagrass fauna (Unsworth et al. 2019*a*). However, gaps in the understanding of Indo-Pacific seagrass social-ecological systems pertain to the global challenges for seagrass conservation (Unsworth et al. 2019*b*). In the Indo-Pacific, seagrass meadows are threatened by a myriad of stressors, including localized threats (e.g., overfishing, seaweed cultivation) and regional and global challenges (e.g., poor water quality, coastal development). Localized threats, although small in impact, can happen over such large spatial and temporal scales (Unsworth et al. 2018) that they make seagrass meadows highly vulnerable to change (Grech et al. 2012). These local threats are commonly overlooked in science and policy and can often arise as unintended consequences of sustainable development initiatives.

A social-ecological systems approach to understand sustainable development initiatives in seagrass ecosystems

Based on the broad knowledge of social-ecological systems (e.g., Folke 2006, Ostrom 2009), we conceptualize Indo-Pacific seagrass ecosystems as a coupled system consisting of two main subsystems, the social and the ecological, which each comprise a further two core subsystems (McGinnis and Ostrom 2014). The social subsystem comprises governance systems and actors, such as government organizations, NGOs, and local fishing communities; ecological system comprises a resource system and resource units, such as seagrass meadows and the fauna they support (Fig. 1). We emphasize that this structure is one of many ways of conceptualizing social-ecological systems, and we use it for our study because of its focus on actors and ecosystem services generation.

We define sustainable development initiatives as any intervention or activity designed either to eliminate poverty, to ensure sustainable lifestyles for all, or to foster a stable and resilient planetary life-support system, as per the overarching aims of the Sustainable Development Goals (Griggs et al. 2014). Sustainable development initiatives may occur within the focal social-ecological system (e.g., changing any of the four subsystems), but because of the interconnected nature of tropical marine seascapes, these initiatives may also have causes and consequences that occur outside the seagrass social-ecological system (e.g., coral reefs, mangrove forests). While not specifically part of the seagrass ecosystem, the characteristics of these other systems are interrelated and play significant roles in sustaining seagrass meadows (Nagelkerken 2009). In both cases (within and outside the system), sustainable development initiatives aim to redefine the linkages within the social-ecological system to achieve a certain goal, ultimately leading to a change in feedbacks, some of them positive (self-reinforcing) and some of them negative (stabilizing). These changes also connote the potential to degrade and disrupt the social-ecological system (Sterman 2000).

Fig. 1. Social-ecological system framework used to understand and interpret unintended consequences of sustainable development initiatives for seagrass meadows in the Indo-Pacific region. Adapted from McGinnis and Ostrom (2014). Dashed arrows represent unintended effects.



Defining unintended consequences from a social-ecological systems perspective

We here define unintended consequences as unanticipated effects brought about by sustainable development initiatives. In our analysis, we refer to the three types of unintended effects inspired by Larrosa et al. (2016), which draw upon disturbance responses introduced by Schoon and Cox (2012). These effects can be singular or multiple to result in an unintended consequence. The three effects we draw upon are as follows.

1. *Flow effects* occur due to changing the strength (enhancing or dampening) of pre-existing linkages within the social-ecological system, brought about by the sustainable development intervention. For example, interventions to alter (increase or decrease) the abundance of individual resource units (fauna) can alter the effect that these individuals play in structuring resource systems.
2. *Deletion effects* occur when pre-existing linkages within the social-ecological system are lost due to the sustainable development intervention. For example, prohibiting actors from accessing resource units or resource systems represents a loss of an important feedback loop.
3. *Addition effects* occur when sustainable development initiatives introduce new elements (variables or relationships) to the social-ecological system structure. Many interventions facilitate the addition of new actors, institutional structures, or resources, which can completely change the structure and function of the pre-existing social-ecological system.

Selection of unintended consequences case studies

We first sought to identify cases of unintended consequences within the peer-reviewed and grey literature for seagrass ecosystems, specifically searching for knock-on (cascading) effects and feedbacks that occurred as a direct result of targeted human interventions. We also searched the Regime Shifts Database (https://www.regimeshifts.org/), a platform containing > 300 specific case studies related to regime shifts and changes in social-ecological systems, for cases documenting targeted interventions that affected seagrass ecosystems. We found few documented cases of unintended consequences within seagrass social-ecological ecosystems, and most of the literature concerning feedbacks relates to naturally occurring ecological feedbacks or shifts due to anthropogenic stresses.

As a result of this information gap and due to the novel nature of our study, we decided to implement an expert-elicitation approach (Caley et al. 2014) to produce expert judgment on the topic (Martin et al. 2012). The procedure followed a standardized five-step approach: deciding how information will be used, determining what information to elicit, designing the process, performing the elicitation, and translating the information into quantitative statements (Martin et al. 2012). We decided that information would be used to provide expert judgment on unintended consequences of sustainable development initiatives, and we sought to elicit known or potential cases of unintended consequences that were not well defined within the literature. We defined experts as individuals with "relevant and extensive or in-depth experience in relation to a topic of interest" (Krueger et al. 2012) and involved experts (all coauthors) with > 100 years of combined expertise studying seagrass ecosystems (both from social and ecological lenses) in the Indo-Pacific region. In February 2020, we facilitated discussions to elicit unintended consequences and identified five potential cases for inclusion in which sustainable development initiatives have or could have the potential to increase the occurrence of seagrass loss, exacerbate seagrass threats, and affect local communities reliant on seagrass resources (Table 1).

Literature sources were then gathered for each of these unintended consequences (Table 1) using the search browser Google Scholar in March 2020 and again in May 2021 and combining keywords related to "seagrass" and the sustainable development initiatives (i.e., turtle conservation; seaweed farming; mosquito nets). One of the cases we identified had plausible unintended consequences (mangrove afforestation), but the literature available did not allow us to explore them further from a social-ecological perspective. We thus used the remaining four initiatives to form the basis of our study.

RESULTS AND DISCUSSION

Using expert knowledge to inform expert judgment, we identifed unintended consequences of sustainable development initiatives for seagrass social-ecological systems across the Indo-Pacific region. Using a seagrass ecosystem lens, the cases were selected to demonstrate direct ecological and social initiatives within the social-ecological system (megafauna conservation and alternative livelihood programs), indirect initiatives within the system (malaria prophylaxis), and initiatives in distant systems (marine protected areas). Here, we show how sustainable development initiatives feed back (through flow, addition, and deletion effects)

Table 1. Sustainable development initiatives with potential unintended consequences for seagrass social-ecological systems in the Indo-Pacific region, identified using an expert-elicitation approach.

Sustainable development initiative	Unintended consequences	Key papers
Megafauna conservation	Overgrazing, regime shift, seagrass loss, conflict	Arthur et al. (2013), Kelkar et al. (2013), Christianen et al. (2014), Heithaus et al. (2014)
Alternative livelihood program	Supplementary income invested in fishing, seagrass loss, encroachment on fishing habitat, species composition change	Eklöf et al. (2005, 2012), Fröcklin et al. (2012), Hill et al. (2012)
Mosquito net malaria prophylaxis	Repurposing as fishing gear, fisheries overexploitation	Short et al. (2018), Trisos et al. (2019), Jones and Unsworth (2020)
Marine protected areas	Displacement, community conflict, fisheries overexploitation	de la Torre-Castro and Lindström (2010), Unsworth et al. (2014), Exton et al. (2019)
Mangrove afforestation	Incorrect restoration location, seagrass loss, encroachment on fishing habitat	Primavera and Esteban (2008), Sharma et al. (2017), Mendoza et al. (2019)

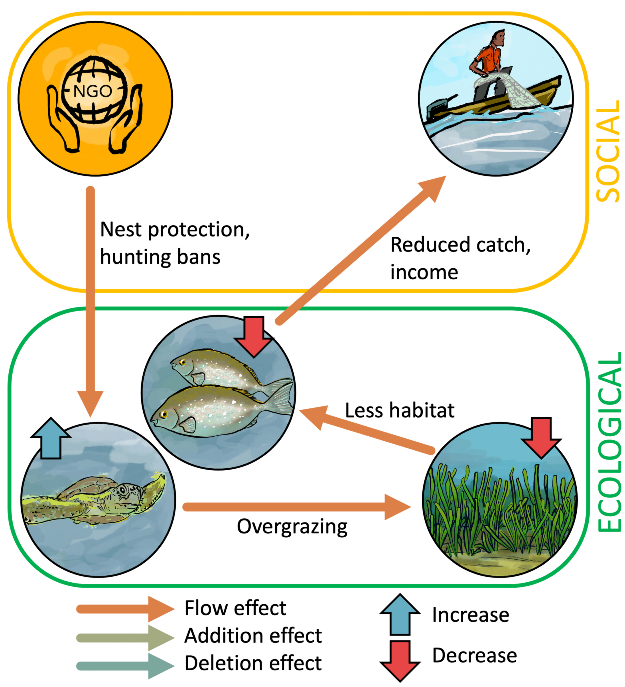
to create new problems or undermine the initiatives themselves. For example, the unintended consequences of turtle conservation result in feedbacks that increase human-wildlife conflict and cause seagrass loss; seaweed farming programs initiated to reduce fishing effort can feed back to increase fishing activity; the distribution of mosquito nets feeds back to undermine the initial goal of the initiative; and marine protected areas result in unintended effects that lead to sequential ecosystem degradation. However, this is not an exhaustive list of sustainable development initiatives with unintended consequences for seagrass social-ecological systems. Multiple other initiatives likely exist across the Indo-Pacific (e.g., mangrove restoration in seagrass meadows) and globally (e.g., seahorse protection conflicting with recreational boat users).

Unintended consequences of charismatic megafauna conservation

Sustainable development initiatives focusing on biodiversity conservation predominantly focus on well-known, charismatic species or high-profile issues (Small 2011). Politicians, members of the public, and NGOs are sympathetic to the so-called flagship or iconic species or habitats. Megafauna are classic flagships (Clucas et al. 2008) that exemplify public engagement with biodiversity conservation (Walpole and Leader-Williams 2002). Because of their appeal, they can be used to rally public attention toward broader conservation objectives (Mazzoldi et al. 2019) such as habitat loss or overfishing. This strategy has long been used by many conservation NGOs (Mazzoldi et al. 2019). However, campaigns and projects promoting flagship species tend to direct the majority of funds exclusively toward recovering populations of those species (Smith et al. 2012). For seagrass meadows in the Indo-Pacific, one flagship example is the green sea turtle (*Chelonia mydas*). Many of the strategies used to promote green sea turtle conservation are potentially inadequate to conserve seagrass social-ecological systems.

Green sea turtles remain threatened (Mazaris et al. 2017), yet sustainable development initiatives that protect turtle nesting beaches and reduce fishing pressure have been highly successful (Chaloupka et al. 2008, Kittinger et al. 2013), leading to a predominantly increasing trend for sea turtle populations across the globe (Mazaris et al. 2017). However, such success comes with a caveat. In many areas, turtle populations are largely released from predation because of a decline in sharks (Heithaus et al. 2012), and research has shown that actions that ignore this effect would result in unintended consequences (Burkholder et al. 2013). For seagrass systems, green sea turtle conservation has generated "flow effects", whereby green sea turtles have grown beyond historical carrying capacity in some areas (Fig. 2), inducing overgrazing of seagrasses and trophic cascades from seagrass loss (Lal et al. 2010, Kelkar et al. 2013, Christianen et al. 2014). Such effects, with the long-term potential collapse of seagrass (e.g., Fourqurean et al. 2019), undermine the long-term sustainability of the turtle conservation initiative through a loss of their food source. However, such initiatives also have societal effects. Structurally complex seagrass areas support higher populations of fish (Jones et al. 2021), and excessive turtle grazing, through a flow effect, undermines this habitat provisioning (Scott et al.

Fig. 2. Conceptual diagram of the potential unintended consequences of megafauna conservation for seagrass social-ecological systems.



2020). It is well known that highly grazed seagrass areas lose important fauna, including fisheries species (Johnson et al. 2020, Inoue et al. 2021). Therefore, the loss or collapse of seagrass structure poses significant well-being risks for fisherfolk who depend on seagrass and associated species as a source of food security or livelihoods through further flow effects (Arthur et al. 2013). For example, the unintended consequence of turtle conservation in the Lakshadweep archipelago increased human-wildlife conflict (Arthur et al. 2013) because of impacts to livelihoods. Fishers lost income and suggested culling turtles and destroying nests as solutions; such actions would undermine the sustainable development initiative.

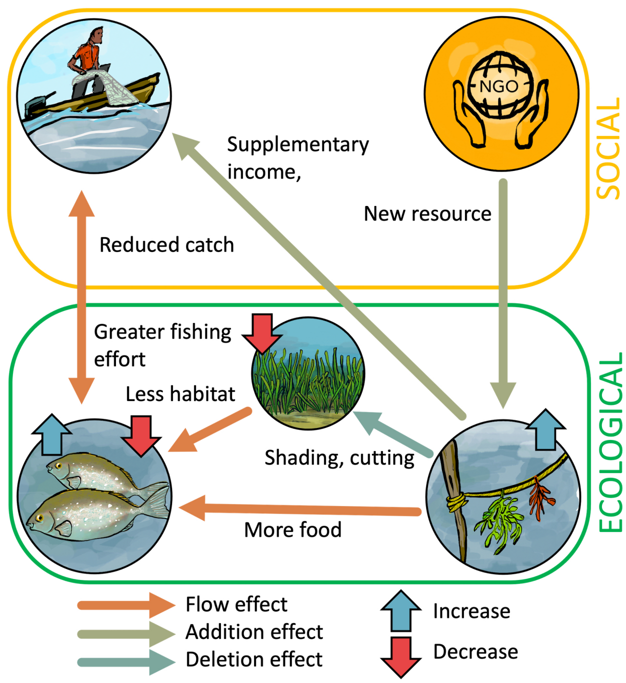
This case also raises geopolitical debate. Because green sea turtles may migrate up to 4000 km from the locality of the conservation initiative (Hays et al. 2014), sustainable development initiatives in one country may have far-reaching unintended consequences for countries that exacerbate existing conflicts. Such unintended consequences may not just relate to fisheries but also to climate change strategies, especially where coastal blue carbon ecosystems are included as "Nationally Determined Contributions" submitted to the United Nations Framework Convention on Climate Change as climate mitigation or adaptation solutions (Herr and Landis 2016). Numerous countries within the Indo-Pacific specifically include coastal ecosystems within their Nationally Determined Contributions (Martin et al. 2016), including Bahrain, Kiribati, Mauritius, Sri Lanka, Sudan, United Arab Emirates (United Nations Environment Programme 2020), and, more recently, Kenya (Kairo and Langat 2021), that specifically reference seagrass meadows. Excessive turtle grazing decreases future carbon sequestration potential through a reduction in net ecosystem production (Johnson et al. 2017). Thus, there is a risk that conservation initiatives in one country undermine climate change mitigation and adaptation strategies in others.

Unintended consequences of introducing alternative livelihoods such as seaweed farming

The historical top-down conservationist archetype imposed by both scientists and NGOs has been replaced in recent decades by involving the rights and needs of communities (Campbell et al. 2010). This paradigm shift toward people-centered conservation occurred because of concerns about the burden that conservation initiatives place on local communities (Sunderlin et al. 2005) and introduced sustainable development initiatives that aim to change or improve livelihoods (Sievanen et al. 2005). Alternative livelihood projects are one such intervention that aims either to reduce reliance on nature, to generate new wealth streams, or to increase support for conservation (Roe et al. 2015). Fishers may already engage in multiple alternative livelihoods such as farming, selling groceries, or working as laborers (Silas et al. 2020), but alternative livelihood programmes generally prioritize new, market-based livelihoods not currently present in the area (Roe et al. 2015). After a commercial success in the Philippines, seaweed farming became an alternative livelihood strategy to fishing that is still championed by NGOs, managers, and senior policy makers for use in low-income and emerging economies (Sievanen et al. 2005). However, seaweed cultivation as an alternative livelihood has multiple and often negative effects in seagrass systems.

Seaweed farming as an alternative livelihood strategy transforms seagrass systems to a large extent by manipulating the seagrass meadow and, through "addition effects" creates a new resource system (i.e., seaweed; Fig. 3). Commercial manuals for seaweed farming advocate placing "growth ropes" on top of seagrass meadows (Neish 2003), altering the structure and function of the seagrass below (Eklöf et al. 2005, 2006*b*). "Deletion effects" occur whereby seagrass is lost or severely affected by seaweed farms (Eklöf et al. 2006*b,* Lyimo et al. 2006, Mallea et al. 2014, Hedberg et al. 2018) or by manipulation by seaweed farmers (de la Torre-Castro and Rönnbäck 2004, Lyimo et al. 2006). The activity significantly affects seagrass faunal communities and the provision of seagrass ecosystem services (e.g., loss of access to target species or fishing ground). For fauna, flow effects are multiple, with increases in siganid fish abundance (Eklöf et al. 2006*a,* Hehre and Meeuwig 2016, Anyango et al. 2017), but decreases in other fish species (Eklöf et al. 2006*a,* Hehre and Meeuwig 2015) coupled with a loss of important invertebrates (Eklöf et al. 2005, Moore et al. 2012).

Fig. 3. Conceptual diagram of the potential unintended consequences of seaweed farming as an alternative livelihood program on seagrass social-ecological systems.



Even ignoring these potentially severe ecological risks, as well as conflict for space, seaweed farming as a sustainable development intervention to reduce fishing pressure has very little evidence of success (Hill et al. 2012). Seaweed farming introduced to reduce fishing pressure creates pull factors for women and children, rather than men (Larson et al. 2021), through addition effects from new income streams, resulting in household incomes being supplemented rather than reducing male fishing (Sievanen et al. 2005). As a result, the supplementary income may maintain or even increase fishing effort through a flow effect from increased monetary investment (Sievanen et al. 2005). Such programs ignore that people's attachment to fishing is more than economical (Bavinck et al. 2012, Cinner 2014), and cultural institutions can be determinants for fishers' behavior (de la Torre-Castro and

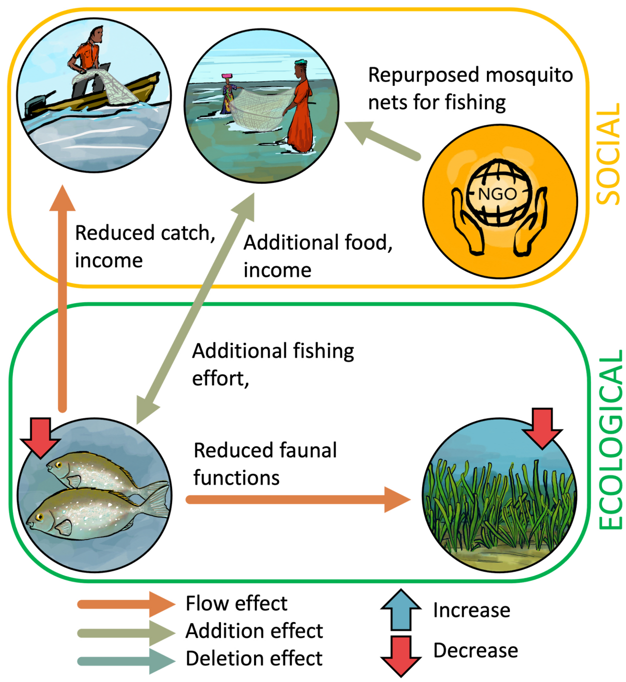
Lindström 2010). Although seagrass fisheries provide income and subsistence, they are strongly associated with culture and personal identity (de la Torre-Castro and Rönnbäck 2004). In addition, in places such as Zanzibar, where in-depth studies have been conducted on the effects of seaweed farming for women, important social identifiers have been negatively affected (e.g., Fröcklin et al. 2012, de la Torre-Castro et al. 2017), with positive effects only for particular individuals (Msuya and Hurtado 2017). Fröcklin et al. (2012) analyzed the intervention as a development project and found that women had considerable health and occupational problems as well as income below the poverty line; in light of these results, the overall benefits of the activity, as well as its sustainability, can be questioned (for review, see also Eklöf et al. 2012).

Unintended consequences of mosquito net malaria prophylaxis in coastal communities

Malaria, with > 229 million cases and 409,000 deaths in 2019 (World Health Organization 2020), remains one of the most monumental health crises of recent times. To ensure healthy lives and promote well-being (SDG 3), NGOs and governments have invested billions in the prevention and control of malaria. Ending the epidemic by 2030 is a key target of the SDGs (target 3.3), and as a result, large-scale initiatives distribute hundreds of millions of insecticide-treated nets across the globe each year. In 2019, > 400 million nets were distributed globally, with coastal countries across the Indo-Pacific region receiving a large share of this total: Indonesia (3.7 million), Madagascar (2.5 million) Mozambique (10.2 million), Myanmar (4.8 million), Papua New Guinea (1.1 million), and Tanzania (8 million; World Health Organization 2020). Although these nets are intended for malaria protection, it has been documented that they are frequently used as fishing gear (Short et al. 2018), generally targeting seagrass-associated fauna (Jones and Unsworth 2020), and they can be one of the most commonly used fishing gears in certain areas such as Mozambique's long coastal area (Samoilys et al. 2019).

Free mosquito net distribution has proven to be very efficient to reduce the rates of malaria (Berthe et al. 2019), but when not used as a mosquito net or when broken, they can provide people (often women and children) with an opportunity to repurpose mosquito nets as fishing gear to enter finfish fisheries (Short et al. 2020) and provide greater access to marine resources for the poor and unskilled (Berthe et al. 2019). This addition effect increases the number of fishers using the seagrass resource system (i.e., provides a new way to extract fish; Fig. 4). Flow effects follow, with potential overharvesting of fauna, which could lead to regime shifts that undermine the long-term viability of the resources in situations with very high fishing pressure (e.g., Vieira et al. 2020). Because of the small mesh size, mosquito nets remove fry and small fish (Jones and Unsworth 2020), which jeopardizes the balance of food webs and compromises full fish growth and further recruitment in systems already suffering from fisheries overexploitation. For people, however, eating whole small fish is beneficial because small fish contain large amounts of vital micronutrients such as calcium, iron, zinc, and vitamin A (Kawarazuka and Béné 2011). Consuming such fish therefore has the potential to contribute significantly to curbing malnutrition (Hicks et al. 2019), especially considering the balanced harvest principle (Garcia et al. 2012). Because fishing with mosquito nets potentially has ecological risks (Jones and Unsworth 2020), their use should be monitored to avoid unintended negative consequences on the environment. However, other flow effects provide short-term opportunities that alleviate poverty (e.g., provide income) and could increase gender equity (e.g., rights and access to fishing grounds; Bush et al. 2017, Short et al. 2020). Actors that use mosquito nets for fishing instead of malaria protection are driven by a series of pull factors (incentives) such as ease of access, ease of use, and reliability of catch, as well as push factors (desperation) such as poverty and declines in alternative resources (Short et al. 2018). A degraded environment that cannot deliver the needed resources might cause even greater malnutrition and poverty; thus, it is crucial to use sustainable fishing gear.

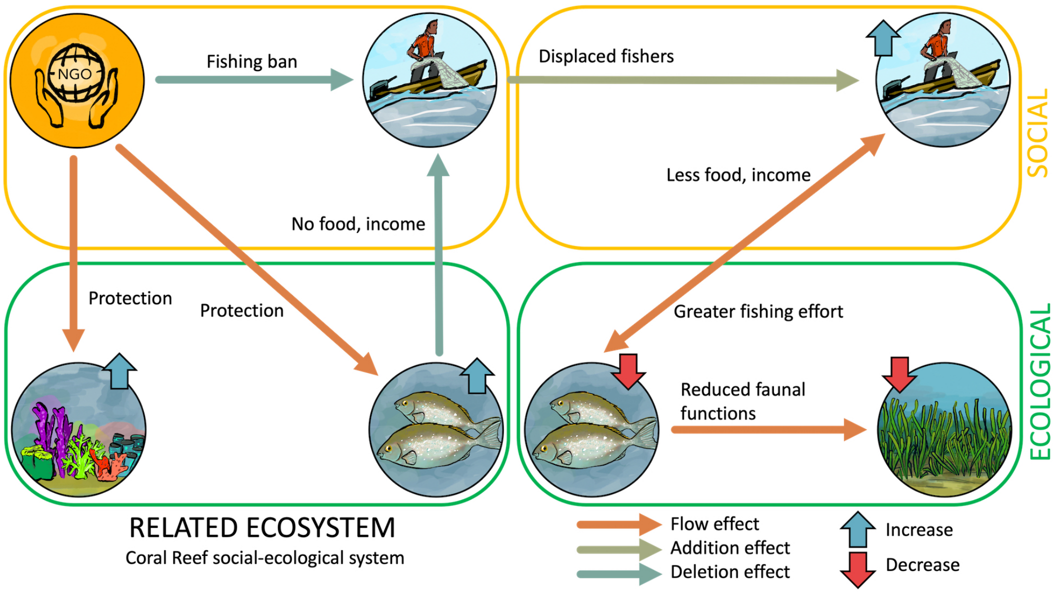
Fig. 4. Conceptual diagram of the potential unintended consequences of mosquito net malaria prophylaxis on seagrass social-ecological systems.



Unintended consequences of establishing marine protected areas

Marine protected areas (MPAs) either use area-based targets to conserve biodiversity (e.g., SDG14) or foster sustainable resource use, improving fishery yield, for example (target 14.4; McClanahan et al. 2006), and have been driven by many international and local actors supported by research results (McClanahan 2011). MPAs normally increase abundance and biomass of fish (Maypa et al. 2002) and may (at least in theory) have "spillover" effects to adjacent fisheries (McClanahan and Mangi 2000, Russ et al. 2003). Considered a "best approach" to fisheries management by some (Johnson et al. 2013), there has been a drive for their placement in low-income and emerging economies. However, many MPAs have been misplaced, with limited ecological function (Jantke et al. 2018) and, more importantly, they can be considered "social failures" because of societal harm such as conflict (e.g., between dive operators and

Fig. 5. Conceptual diagram of the potential unintended consequences of marine protected areas on seagrass social-ecological systems.



fishers), economic loss (e.g., loss of livelihoods), and dislocation of disadvantaged communities (e.g., fishing communities living within MPAs; Christie 2004, Mascia and Claus 2009, Agardy et al. 2011).

Many tropical MPAs focus on imposing no-take areas or using gear restrictions (Hargreaves-Allen et al. 2017), yet seagrass meadows are rarely included in these targets to reduce fishing (Nadiarti et al. 2012) despite emerging recognition of the value of seagrass fisheries (Nordlund et al. 2018). Some MPAs fail by assuming that previous fishing effort just disappears, whereas it is often displaced and potentially concentrated elsewhere (Kaplan et al. 2010). The implementation of gear restrictions or no-take areas can result in a deletion effect within a nearby system (e.g., coral reef system) and an addition effect within the seagrass system (Fig. 5). Fishers no longer have access to the fauna or fishing habitats within the nearby system (e.g., coral reef system) and are thus displaced (Cinner et al. 2014), in this case, to seagrass meadows. For example, following gear restrictions and reserve creation in Kenya, fish catches showed increased composition of juvenile seagrass-associated scavengers and herbivores such as *Lethrinus, Leptoscarus,* and *Siganus* spp. (McClanahan et al. 2008, Hicks and McClanahan 2012). Similarly, after destructive fishing methods (e.g., dynamite) on coral reefs were banned in the Wakatobi National Park, Indonesia (von Heland and Clifton 2015), the contribution of seagrass-associated fish to livelihoods and food security became more apparent (Unsworth et al. 2014). However, this increased fishing pressure presents a risk. Overharvesting of seagrass-associated fish species presents a flow effect that threatens the seagrass resource through reduced resilience and, in turn, could create community conflict (de la Torre-Castro and Lindström 2010, Exton et al. 2019) or contribute to seagrass decline (Harcourt et al. 2018, Unsworth et al. 2018). The move of fishers to an adjacent system also presents opportunities whereby communities can continue to collect the marine resources needed to support livelihoods and food security following the loss of access to original fishing grounds (Cullen-Unsworth et al. 2014). That being the case, sustainable fisheries in seagrass areas should be promoted and non-damaging practices encouraged. The implementation of payments for ecosystem services schemes could also provide new opportunities for sustainable development.

Problems arising

Common to all sustainable development initiatives that we discussed is the apparent lack of knowledge and understanding from NGOs and implementers; it is normally not recognized that seagrass meadows are an intrinsic part of the social-ecological system in which the intervention sits. Initiatives to reduce overfishing (e.g., alternative livelihoods, MPAs) as well as those to conserve biodiversity (e.g., turtle conservation) have failed to take an ecosystem-based approach or acknowledge that so-called "reef fisheries" (Ruddle 1996) are broader seascape fisheries with several links to other ecosystems. Specifically, the fact that seagrass meadows are used as a fishing ground by many is ignored. Recent research demonstrates that seagrasses act as fishing grounds globally (Nordlund et al. 2018), but failing to acknowledge this fact means that they remain marginalized in policy (Unsworth et al. 2019*a*). Fishers that use seagrass may be the poorest in society because of their strong dependence on the habitat for food and livelihoods (Cullen-Unsworth et al. 2014, Quiros et al. 2018), yet discussions around conservation, management, and sustainable development in general still fail to reflect the perspectives of the communities that will be affected (Belhabib 2021). Therefore, using local and traditional ecological knowledge should be prioritized when planning sustainable development initiatives.

Another key process that we identified were unexpected behaviors by communities. These behaviors arise due to emergent properties that are difficult to predict or account for (Glaser et al. 2012), as in the cases of mosquito net fishing and seaweed farming. For both cases, socioeconomic issues are assumed to be black and white, presuming that ill health is the only barrier to livelihood generation (e.g., malaria) or that poorer households just need different jobs (e.g., alternative livelihoods). Although both statements may be true in specific contexts, their assumptions marginalize culture and identity and result in "taboo trade-offs" that ignore the often-sacred value of fishing as a right or a social recreation activity (Daw et al. 2015). Such unexpected behaviors, especially in the context of pull factors, are common for fishing communities. In Zanzibar, for example, even when presented with alternatives, communities continued to use destructive and illegal fishing gear because information on the advantages of sustainable gear (i.e., financial and cultural benefits) were scarce and because illegal gear is associated with strong comradeship and signals youth and strength (Wallner-Hahn et al. 2016).

Planning, anticipation, and remediation

To identify these risks, in-depth social impact assessments are required that consider both the positives and negatives of proposed initiatives in the context of social-ecological systems. This process demands a willingness to question narratives of sustainability and reexamine existing initiatives for unintended consequences (Short et al. 2020). Using adaptive approaches to implementation (Reed et al. 2006), whereby we monitor more of the social-ecological system spectrum, we could increase the likelihood of identifying unintended consequences and adapting the sustainable development initiative to account for them (Olsson et al. 2004). Evaluating not only the intervention's impact on its target (e.g., turtle populations), but also its impact on the wider social-ecological system (e.g., seagrass abundance, fish abundance, and fish catches), would help us understand and identify the true drivers of successes or failures. For example, when evaluating the success of turtle conservation initiatives, we should not only be monitoring green sea turtle abundance, but also seagrass abundance (e.g., biomass, cover), faunal abundance, fisheries landings, and fishers' opinions. We also need to consider the scale at which monitoring is required, which, for migrating sea turtles, can be extremely large (Hays et al. 2014). Such monitoring could suggest the possibility that top predators (e.g., tiger sharks) also need to be restored to avoid unintended consequences (Heithaus et al. 2014). Well-designed, robust, social-ecological monitoring would not only help to identify unintended consequences but would also help to build evidence on the types of unintended consequences that are common in similar systems. However, identifying the presence of unintended consequences in project outcomes requires robust data from all subsystems (Short et al. 2020) and, ultimately, more resources allocated to such investigations.

Given the strong association between environmental degradation and food insecurity, poverty, and well-being (Subramaniam and Masron 2021), ignoring social factors and communities in general within these social-ecological systems would only disenfranchise local actors further (Belhabib 2021). However, by building resilience into sustainable development initiatives, i.e., the capacity to change, learn, and develop (Folke et al. 2002), there is potential to harness unintended consequences to help further the SDGs in the context of seagrass social-ecological systems. For example, in some countries, top-down approaches make the use of mosquito nets for fishing illegal (Blythe et al. 2013), but it does nothing to tackle underlying pull factors that result in mosquito nets being used for fishing in the first place (Trisos et al. 2019). One way to handle the unintended consequence could be to promote inclusive management (de la Torre-Castro 2019) in which the role of women is acknowledged. Women using mosquito nets can then be involved in gear-exchange programs, rather than fined or jailed, and included in local coastal spatial planning. Transitioning mosquito net fisheries, which are dominated by women, to a more sustainable fishery works toward fulfilling social goals (e.g., SDG1 Zero Poverty, SDG2 Zero Hunger, SDG3 Good Health and Well-being, SDG5 Gender Equality), economic goals (SDG8 Decent Work and Economic Growth, SDG12 Responsible Production and Consumption), and environmental goals (SDG14 Life Below Water). Such an opportunity highlights the need to be holistic in the monitoring, design, and implementation of sustainable development initiatives and take a "full-spectrum sustainability" approach that considers social, ecological, and economic factors equally (Foley et al. 2020). It is not necessary to avoid sustainable development initiatives for fear of unintended consequences; we see such consequences as learning opportunities to strengthen and adapt current initiatives.

CONCLUSION

Piecing together evidence from multiple locations across the vast Indo-Pacific region, we have documented how sustainable development initiatives alter seagrass social-ecological systems through flow, addition, and deletion effects, resulting in unintended consequences for both people and nature. We present risks and potentially severe unintended consequences (e.g., overfishing, habitat collapse, regime shifts) that, in some cases, undermine the sustainable development initiative. However, we also reveal how unintended consequences present opportunities for learning and for actions to be transformed toward sustainability to help further the SDGs (e.g., biodiversity conservation, poverty alleviation, livelihoods, and gender equity). Our analysis revealed that unintended consequences arise through failing to acknowledge parts of the social-ecological system in which the initiative occurs or by neglecting that certain behaviors and activities are cultural. Strong sustainability strategies are needed to tackle the societal and environmental challenges of the Anthropocene if we are to meet the goals of 2030 Agenda (Díaz et al. 2020), but systems thinking is required to avoid unintended consequences.

In the context of current policy and the United Nations Decade of Ocean Science for Sustainable Development (Claudet et al. 2020), our findings highlight the need to use social-ecological monitoring frameworks to ensure that initiatives are positive for both people and nature, not just for seagrass social-ecological systems, but for all systems. For current and past initiatives, we urge implementors and funders to consider not just focal organisms or individuals, but the whole system, in monitoring and evaluation. Doing so will no doubt identify failures but will also highlight opportunities for dialogue and learning. For future policy, we suggest that implementors consider an a priori process for identifying potential unintended consequences, using local and traditional ecological knowledge to improve sustainable development practice and foster progress to meet the goals of

2030 Agenda. Unintended consequences will always be present, but rather than ignore them because they are outside the scope of initiatives or programs, we must acknowledge and actively lessen these effects to enable transitions to sustainability.

Responses to this article can be read online at:
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