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Article

A Multi-Scalar Examination of Law for Sustainable Ecosystems

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Abstract: The loss of resilience in social-ecological systems has the capacity to decrease essential ecosystem services, posing threats to human survival. To achieve sustainability, we must not only understand the ecological dynamics of a system, such as coral reefs, but must also promulgate regulations that promote beneficial behavior to address ecological stressors throughout the system. Furthermore, laws should reflect that systems operate at multiple spatial and temporal scales, thus requiring management across traditional legal jurisdictions. In this paper, we conducted a multi-scalar examination of law for sustainable ecosystems and how law pertains to coral reef ecosystems in particular. Findings indicate that, in order to achieve sustainability, we must develop new or reform existing legal mechanisms to protect ecosystems.

Keywords: resilience; environmental law; coral reef ecosystems; sustainability

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1. Introduction

Sustainability has many definitions, but one of the more commonly used definitions is meeting "the needs of the present without compromising the ability of future generations to meet their own needs" [1]. Ultimately, sustainability is an anthropocentric issue that expresses the need for maintaining economic, social, and supporting environmental systems over the long term for the benefit of humankind [2]. Supportive environmental systems provide humans a number of ecosystem services, such as pollination, fermentation, and temperature regulation—vital functions to humans that are critical to sustainability [3,4]. For this article, we link our definition to the conditions necessary for the resilience of ecological systems, because resilience implies the persistent provision of ecosystem services. Loss of biodiversity, for example, has the capacity to erode the resilience of conditions favorable to humankind, as it can lead to the degradation or loss of ecosystem services critical to human survival [5]. Fortunately, ecosystems have inherent resilience and can persist under some human-induced stressors, but under enough stress, resilience will likely degrade to a point where we will lose ecosystem functions (e.g., nutrient cycling or soil development) and services. To achieve sustainability, we must protect these ecosystem services and not damage ecosystem functions to such an extent that the systems fail to function in a desired manner.

In order to achieve sustainability, adequate protection of ecosystems depends on the implementation of sound environmental law [6]. As a first step, policy must be based on sound scientific research. To manage ecosystems, we must "measure the flows of these services, examine who is benefiting from them," and only then can we "consider a range of policies, incentives, technologies, and regulations that could encourage better management and sharing of the benefits" [7]. In this article, we first illustrate aspects of ecological systems that contribute to system resilience by focusing on coral reefs as an example of these principles, though these principles apply to many different systems. Second, we provide an overview of current legal mechanisms and those with potential to protect coral reef ecosystems and the services they provide. This paper explicitly accounts for the multi-jurisdictional, trans-boundary nature of sustainability, and considers the legal conditions necessary for fostering resilience and maintaining ecosystem services.

Resilience

Ecosystems have evolved interrelated, redundant subsystems that increase their resilience [8]. An ecosystem is resilient and maintains its characteristic properties, or regime, unless perturbations overwhelm the system and a threshold or tipping point is reached [9]. An ecological threshold is the point at which an ecosystem experiences a major shift in quality (for better or worse), system properties, or phenomena from a disturbance or environmental driver [10]. Within the context of sustainability, ecosystems are more resilient when the thresholds between dynamic regimes are higher (*i.e.*, larger disturbances are necessary to shift between regimes) [11]. The result is a strong link between resilience and sustainability [12].

Several models have been proposed to explain resilience, including the cross-scale resilience model, which explains resilience as the result of diverse, overlapping functions within a temporal or spatial scale and seemingly redundant species operating at different temporal or spatial scales [13]. Overlap and redundancy reinforces function across scales and results from biodiversity [13]. Although biodiversity is a scale-dependent property (*i.e.*, changing the temporal or spatial context will likely result in a change in biodiversity) and includes all hereditarily based variation from genes in a single population up through the communities of ecosystems [14], all biota, including humans, interact with the environment at distinct scales and create self-organizing patterns [15].

Simply stated, individuals going about their daily business of survival utilize resources at specific spatial and temporal scales. Through natural selection processes, the population may evolve competitive advantages to exploit available resources when individuals that are better suited to exploit a particular scale pass those traits on to their offspring and produce more offspring (e.g., increased fitness). Natural selection shapes populations, which leads to increased distinction between scales, resulting in multiple but distinct scales of self-organization. The ensuing distribution of function within and across temporal and spatial scales creates resilient systems [13]. Thus, system resilience depends upon interactions between structure and dynamics at multiple scales [16]. Moreover, if ecosystems degrade to such an extent that they are no longer resilient, sustainability cannot be achieved, because we will lose the services and functions they inherently provide. Resilience gives an ecosystem the ability to withstand our insults and continue to provide resources necessary to support humans.

Resilience both depends on a system's functional diversity (*i.e.*, the number and variety of functions within an ecosystem, or what organisms "do" in an ecosystem) (see [17] for a general overview) and on the range of responses (*i.e.*, response diversity) within functional groups [18,19]. Such diversity results in species with the capacity to fill functions both within and across ecosystems [18]. Functional diversity is an important aspect of resilience, and when coupled with functional redundancy across scales, generates cross-scale resilience [13]. Functional redundancy manifests when multiple species perform the same ecosystem function and differs from response diversity, as functional redundancy would be inadequate if all species of a functional group interact in the same manner [19]. Therein lies the benefit of biodiversity and related species diversity (Tables 1 and 2). Species diversity results in greater response diversity and increases resilience by increasing the redundancy of species [20], thus increasing the redundancy in functional traits [21,22]. A system with limited response diversity is susceptible to frequent regime shifts, because the loss of a single species or functional group could result in the disruption of nutrient cycling or energy flow, in extreme cases. Thus, high functional richness and redundancy are insufficient to resist system crashes if redundant species do not respond differently to different stimuli [19,23].

Below (Tables 1 and 2), a simple example is given of how biological diversity leads to resilience and how functional redundancy and functional diversity result from high biological diversity. The species and traits are generic and overly simplified in an effort to explain the concepts. Table 1 describes what a species does (*i.e.*, the functions it performs) and which of the functions are unique or redundant. Example or hypothetical functions, such as provided by a coral reef (although they could be anything in this example), are F1 = erosion control, F2 = controls algae density, F3 = controls coral density, F4=sequesters carbon. Table 2 demonstrates how the loss of one or more species can impact the functions performed in a community and if the community is resilient to the perturbation.

Table 1. Simple sample community and species functions.

Species	Functional Diversity	Functional Redundancy	Sleeping Function
A	F1, F3, F4	F1, F4	F2
B	F1, F4	F1, F4	
C	F2		

Table 2. Alternative communities and relative resilience.

Community	**State 1**	**State 2**	**State 3**	**State 4**
Species composition	ABC	AC	BC	A
Functions	F1, F2, F3, F4	F1, F2, F3, F4	F1, F2, F4	F1, F2, F3, F4
Summary				
Species	All species present	Species B lost	Species A lost	Species B and C lost
Functions performed	All functions performed	All functions performed	F3 not performed	All functions performed, because species A performs F2 when species C disappears (*i.e.*, sleeping function)
Functional redundancy	Redundant functional groups present	No functional redundancy	No functional redundancy	No functional redundancy
Resilience	Resilient	Less resilient	Likely to undergo a regime shift or system crash	Least resilient

2. Coral Reef Ecosystems

The large body of research on biodiversity and aspects of resilience in coral reef ecosystems provides examples of the above concepts in action (e.g., [12,24]). Coral reef ecosystems are amongst the most productive and biologically diverse systems on the planet and provide critical ecosystem services (e.g., recreation, tourism and capture fisheries, buffer zones in coastal regions, nursery habitat for marine species) [3]. Coral reef ecosystems appear resilient to natural disturbances (e.g., tropical storms, predation), but lose resilience when facing intense anthropogenic threats (e.g., overfishing, pollution) [12,24].

Coral reef ecosystems exhibit spatial resilience when they withstand perturbations at a regional scale, as opposed to the resilience of an individual reef [25]. Resilience of these systems depends on biodiversity—genetic variability, the functional richness within a scale, the functional redundancy across scales, and the variability of adjacent habitats [25]. For example, Indo-Pacific reefs exhibit greater resilience than Caribbean reefs. One reason might be that despite the fact that the two regions share similar functional groups of species, Caribbean reefs have fewer species and therefore less redundancy within functional groups [25]. When sea urchins (class Echinoidea), the principle herbivore on Caribbean reefs, suffered massive casualties due to a disease outbreak, Caribbean reefs became more vulnerable to perturbations because of a lack of functional redundancy and response diversity [23].

Degradation of many of the world's coral reefs has resulted in regime shifts, whereby the reefs are no longer coral-dominated systems [26]. For example, stressors such as the loss of macro-invertebrates, reduced fish stocks, increased echinoid herbivory, reduced coral recruitment, coral predator outbreaks, and increased terrestrial nutrients and sediment have preceded regime shifts in Caribbean coral reefs [12,26,27]. Whereas the effect of each individual stressor is well known, the cumulative effect of multiple stressors on the resilience of Caribbean reef ecosystems was not anticipated.

As a demonstration of the cumulative effects and importance of biodiversity, Bellwood *et al*. [26] induced a regime shift in a large-scale experiment and found that rapid shifts from a macro-algal-dominated regime to coral- and epilithic algal-dominated regimes were not driven by shifts in the herbivore community. Instead, the regime shift was driven by a single species of batfish (*Platax pinnatus*), which up to that point, was not known to be herbivorous. It was discovered that batfish represent a "sleeping" functional group that performs vital functions only under extreme conditions, such as a regime shift [26]. When macro-algae began to dominate the coral reef and the reef shifted to a less healthy state, batfish began to feed on the macro-algae, thereby improving the health of the coral reef [26]. This suggests that previously unknown functional groups likely play a role in the resilience of many coral reef systems when these are assaulted by multiple stressors [26].

It might seem that maintaining high biodiversity is enough to maintain ecosystem resilience because systems with high species richness and functional diversity should be more resilient to disturbance than systems with low species richness and functional diversity [27,28]. However, individual species of utmost importance (*i.e.*, keystone species) must be protected as well [29]. For example, the importance of critical individual species was demonstrated by Bellwood *et al*. [27] who found the overfishing of and resulting of loss of a keystone species—the giant humphead parrotfish (*Bolbometopon muricatum*)—resulted in reduced resilience in a coral reef with high biodiversity.

Therefore, we must look beyond a simple measure such as species richness as a proxy for resilience, and instead identify and protect species that perform key functions in ecological systems, such as keystone species [27,29]. In a study of coral and reef fish species assemblages in 113 sites in the Indian and Pacific Oceans, Bellwood and Hughes [30] found species composition to be constrained within a narrow range of configurations and a conservative taxonomic composition of coral and reef fishes. This indicates that coral reef assemblages are islands with predictable proportions of coral and reef fish species in a vast matrix of oceans [30]. Thus, maintaining the resilience of coral reef ecosystems requires maintaining large areas of suitable habitat.

Because coral reefs have a patchy distribution, healthy reefs that are not threatened by particular stressors may act as refugia or reservoirs for degraded or threatened coral reefs [31], which means that coral reef ecosystems cannot be successfully managed in isolation [32]. The complex habitats that make up the seascape (e.g., mangroves, seagrass), including metapopulations of coral reefs, must be considered and can be protected only if source reefs are protected [24]. Broader ocean policies and threats, such as overfishing and changing water temperature, have direct impacts on coral reefs and must be included in the policy discussion. Likewise, terrestrial impacts on coral reefs from stressors such as agriculture, urban stormwater, and deforestation must also be part of an integrated solution when managing for resilience.

3. Existing Legal Mechanisms

Environmental law is a necessary means to achieve sustainability, and the forms of policy instruments, governance structures, and legal responses to the inherent variability in social-ecological systems play a vital role [33]. For example, local ordinances may result in spatially small-scale perturbations, such as land clearing and burning of fossil fuels, the consequences of which may contribute to global problems, such as loss of biodiversity and climate change [34]. On the other hand, large-scale legal instruments, such as international treaties, which aim to curb problems of the global commons, may not have their desired impact if they lack enforcement provisions or fail to spur action at the global scale [35]. As the coral reef examples demonstrate, environmental policy should focus on ensuring the resilience of ecological systems, as resilience is necessary for sustainability [36].

In this section, we briefly discuss the role of law in protecting our coral reefs with a particular focus on jurisdiction (legal scale) and resilience. Because coral reef ecosystems are impacted by activities on land and the open ocean, our examination encompasses policy options at multiple levels of management. We begin with the global scale and increase resolution and decrease extent as we move upstream to local upland policies and their potential impacts on coral reef ecosystems (Figure 1). Of the three major stressors to coral reef ecosystems, climate change, nutrients, and overfishing, climate change poses the greatest policy challenge due to the inextricable transboundary nature of the problem. The failure of the international community to reach consensus in addressing this global problem (e.g., Kyoto Protocol, carbon markets) has left us with limited tools to protect coral reefs from climate change impacts (e.g., ocean acidification, temperature fluctuations).

However, domestic solutions, taken together, may buffer some climate change impacts. Examples of climate policy solutions at the national, regional, state, and local scales include: federal tax credits to encourage the purchase of energy efficient products, cooperation among regional players, such as the Western Governors' Association's climate strategy [37], California's statewide cap on greenhouse gas emissions [38], and municipal zoning for mixed use to encourage less vehicle travel and less vehicular emissions. Following the National Oceanic and Atmospheric Administration's (NOAA) Coral Reef Conservation Program, we focus on laws and policies that address fishing and land-based threats in the remaining sections of the paper, as these impacts are more effectively dealt with at a domestic level, though we briefly cover mechanisms for international cooperation in the fishing context [39].

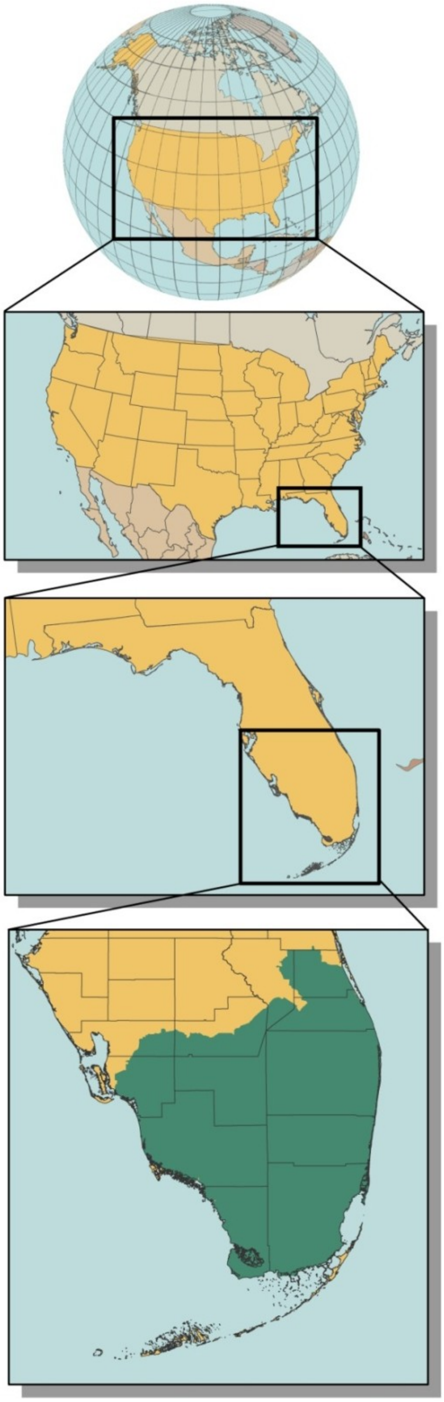
3.1. Global and International Tools

Oceans cover more than 70 percent of the planet and most of this area falls into the jurisdictional category of "high seas". Other than a narrow strip of ocean adjacent to coastlines (≤12 miles), most of the ocean is a "global commons", which is open to all and owned by none [40]. International governing bodies have developed legal frameworks for cooperatively governing the sea with varying degrees of success. Whereas shallow coral reef systems mostly lie within the territorial boundaries of particular coastal countries, activities in the high seas, such as pollution and overfishing, certainly affect health of coral reef systems. Thus, we begin our discussion of legal tools from a global perspective.

The highest profile and most comprehensive ocean governance framework is the United Nations Convention on the Law of the Sea (LOS Convention). The LOS Convention covers a variety of ocean issues, including transportation, fishing, mining, and environmental protection. The environmental provisions concern waste-dumping, pollution, and overfishing and clarify jurisdictional issues relating to the enforcement of domestic and international environmental law. Despite strong bipartisan support, the LOS Convention has yet to be ratified by the United States, making the United States the only major coastal nation that does not belong to the LOS Convention. However, the United States treats the LOS Convention as customary international law and, as such, abides by its substantive principles.

Ratifying the treaty would not require changes to U.S. law but would give the U.S. government a formal seat at the negotiating table when treaty parties meet to determine the direction of ocean policy [41].

Figure 1. This figure demonstrates the challenges of scale in environmental governance of linked social-ecological systems. In this example, coral reef ecosystems (e.g., in the Florida Keys) are impacted by activities on land, freshwater, and sea, and thus protection of reefs requires legal mechanisms at multiple levels. In order to illuminate the potential impacts on coral reef ecosystems we begin with the global scale and increase resolution and decrease extent to the United States, Florida, and the Florida Keys in order to discuss the legal mechanisms that offer promise for sustainability within and across scales.



At a more specific governance scale, the United States has entered into several treaties with other nations concerning particular interests relating to the sea. For example, the United States is a party to the South Pacific Tuna Treaty along with Pacific Island States [42]. The agreement establishes formal cooperation and annual consultations to address issues affecting U.S. fishing vessels in the South Pacific and economic assistance, and serves as a model for international fishery cooperation [43]. Treaties have great potential to determine the resilience of both the cooperative institutions they establish and the natural resources they govern [35,44]. Certain treaty features, such as dispute resolution mechanisms and flexibility in the allocation of resources that reflects natural variability in the quantity available, have been shown to reduce the likelihood of conflict over a shared resource, which may lead to more resilient institutions [45].

3.2. Federal Tools

Several federal laws, regulations, and policies are directly and indirectly relevant to the conservation of coral reefs. Under international law, each coastal nation has jurisdiction over the first 12 nautical miles seaward from the coast, the territorial sea. In the United States, jurisdiction is split between the federal and state governments. Federal jurisdiction begins three nautical miles from the mean low water line along the coasts (nine nautical miles for Texas, Florida's Gulf Coast, and Puerto Rico) as outlined in the Submerged Lands Act of 1953, which granted states authority to manage, develop, and lease resources on and under the seafloor as well as throughout the water column [46]. Beyond the territorial sea lies the contiguous zone, which extends between 12 and 24 miles seaward from the coast. In this zone, nations have limited authority to restrict actions related to customs, immigration, and sanitation. Beyond the contiguous zone lies the exclusive economic zone from 12 to 200 miles beyond the coastline. Within this zone, each coastal nation has exclusive rights to explore, exploit, conserve, and manage all living and nonliving resources in the water, seabed, or subsurface [47].

3.2.1. National Ocean Council

The National Ocean Council, a cabinet-level collaboration between multiple departments and agencies that have some stake in ocean policy, recently released a National Ocean Policy draft implementation plan describing a new, collaborative approach to ocean management (National Ocean Council 2012). The integrated approach recognizes the impact of upstream land-use decisions and practices on our coasts and is centered on ecosystem-based management (EBM). This approach recognizes the interconnectedness within systems and among different systems across a range of spatial and temporal scales. The council acknowledges this federal government-wide implementation as a "major shift in how the Nation considers human uses of ecosystems, moving away from a sector-by-sector approach to management toward a more integrated way of doing business" [48] (p. 2).

While the draft implementation plan does neither create new regulations nor change existing federal authorities and responsibilities, it highlights barriers to full integration of EBM through eroding divisions between agencies and streamlining relevant permitting processes. The council aims to support regional, inter-jurisdictional collaborations and alliances, such as the Governors' South Atlantic Alliance, in their promotion of biodiversity. The council also promotes the exchange of information and expertise between U.S. agencies and international partners to address global issues.

The council has priority objectives, including resilience and adaptation to climate change and ocean acidification. On point, the council highlights coral reefs as among "the most diverse and biologically complex ecosystems on Earth" and the alarming rate at which they are deteriorating [48] (p. 49). As such, the council partnered with the U.S. Coral Reef Task Force to protect and conserve coral reefs from primary stressors with a "ridge-to-reef" approach. The council aims to expand its reach to dryland by identifying and supporting priority land protection and restoration strategies and reducing coastal wetland loss [48].

3.2.2. Coral Reef Conservation Act and Coastal Zone Management Act

The Coral Reef Conservation Act (CRCA) was established in 2000 to preserve coral reef ecosystems, promote sound resource management, and increase the understanding of reef systems by funding scientific studies and restoration projects. CRCA established four major programs, (i) the National Coral Reef Action Strategy to identify goals for research, monitoring, and conservation and address regional and international issues, (ii) the Coral Reef Conservation Program to fund NOAA's coral reef work, (iii) the Coral Reef Conservation Fund to authorize NOAA to distribute grants to nonprofits, and iv) the National Program to assess coral reef conservation [49].

As described in the previous sections, understanding the multi-scale interactions in coral reef ecosystems is vital to sound management and enhancing resilience. As such, CRCA takes vital steps toward increasing the resilience of these systems through research and funding [50,51]. The CRCA is mostly procedural and voluntary, much like the Coastal Zone Management Act (CZMA) of 1972 [52], but encourages coastal states to develop and implement management plans for the protection of coastal resources, including coral reefs. The Act authorized funding for several grant programs aimed at identifying, monitoring, and preserving coastal and estuarine areas and established the National Estuarine Research Reserve Program [52]. While the strategies and management plans include the noble goal of reducing identified threats to coral reefs, there are no mechanisms within the CRCA or CZMA to accomplish these goals aside from funding programs [50]. Thus, we discuss federal policy options that include enforcement provisions in the following sections.

3.2.3. Federal Public Trust in Territorial Waters

One policy option to resolve the conflict between the perceived need for economic growth and conservation is to treat our natural resources much like a fiduciary trust, held for the benefit of the public. Under the public trust doctrine, the state is the trustee and must avoid risks to the trust and manage the trust with a high degree of caution [53]. In fact, trustees must preserve trust principal, suggesting a typical approach of maximizing expected value of the trust is not sufficient [54,55]. Rather, trustees must take a more conservative approach for intergenerational decisions [54]. This is particularly relevant to social-ecological systems, as these have an inherent degree of unpredictability. Ruhl [56] contends that ecosystem services should stand on equal footing with economically valuable uses under the public trust doctrine. The public trust doctrine flows from the English common law and places a duty on the states to preserve natural resources for the benefit of the public [57]. The state, as a trustee, has an affirmative duty to protect natural resources and may not "alienate or extinguish the trust" [58,59].

Although the U.S. Supreme Court has unequivocally rejected the notion of a federal public trust doctrine that applies to dry land [60], Turnipseed *et al*. [61] advocate that a federal public trust doctrine could operate as a mechanism for protecting marine resources (e.g., coral reefs) by entrusting federal agencies with managing these trusts for the benefit of all U.S. residents. Achieving this requires a shift in legal interpretation, as the public trust doctrine extends from the common law and has been established only at the state level [61]. However, there are examples at the state level where the public trust doctrine has been extended to broad-level ecosystem protection [62]. Trust law evolved from the common law and defers to legal precedent, but change is possible because it is also responsive to current norms [54]. Several states have recognized that change is a constant in ecological systems, and thus the public trust doctrine should evolve to deal with new environmental threats and advances in science or our understanding of these systems, such as climate change and ocean acidification [59].

Even if the public trust doctrine cannot be modified in a manner that protects marine ecosystems within the scope of the doctrine, it is possible that ecosystem properties can be reframed within the context of the doctrine. Ruhl and Salzman [63] contend that protected public trust resources typically provide ecosystem services to the public, which therefore should extend protections under the doctrine to the ecosystem services from trust resources enjoyed by the public. Under this interpretation, which is limited to navigable and tidally influenced waters, coral reefs would be afforded protection under the doctrine [63].

3.2.4. National Marine Sanctuaries

Marine sanctuaries are another federal policy mechanism for protecting coral reefs and are commonly referred to as "no take" areas, indicating a ban on fishing in the sanctuary. Federal sanctuaries are authorized by the National Marine Sanctuaries Act (NMSA), which permits NOAA to protect marine areas that hold particular significance due to ecological, recreational, historical, scientific, aesthetic, conservation, cultural, education, and archeological qualities [64]. NOAA has the authority to promulgate regulations for the management of each sanctuary to fit its particular needs. Such regulations often restrict or prohibit certain activities within the protected area and impose civil penalties on violators, though not all illegal activities (e.g., poaching) can be caught and penalized. Further, the National System of Marine Protected Areas is an effort to coordinate the management and protection of reserves to maximize conservation efforts, regardless of whether the reserves fall under federal, state, tribal, or local jurisdiction [64].

3.2.5. Clean Water Act

The Clean Water Act (CWA) authorizes policy options for controlling water pollution and can indirectly benefit coral reef ecosystems. CWA is the primary command-and-control regulatory tool for protecting rivers, lakes, and estuaries in the United States. It prohibits the discharge of pollutants into the waters of the United States without a permit and establishes the National Pollution Discharge Elimination System (NPDES), which grants permits based on industry-specific technology standards and waterbody-specific water quality standards [65].

In order to lawfully discharge, industrial and municipal permit holders must meet technology-based standards that tend to be more stringent depending on the toxicity of the pollutant. For highly toxic pollutants, a permit holder may be forced to install the most effective technology available, regardless of cost, even if it drives the entire industry out of business [66]. Furthermore, if a permit applicant wishes to discharge into a water body that is impaired and/or designated for particular uses, additional restrictions may be included in the permit, even if the applicant already utilizes the industry's technology standard. Designated uses relate to particular water quality goals and identify potential ecosystem services that regulators deem important to that particular stream segment [67]. The connection between protected ecosystem services and designated uses may be indirect as well. For example, attaining the criteria established for fish consumption may enhance aesthetics and recreational services, such as with the protection of coral reefs [68].

In addition to regulating industrial and municipal discharge, CWA jurisdiction stretches to dryland activities, such as construction and agriculture. These nonpoint sources (NPS) of pollution are more challenging to regulate as they are not explicitly prohibited in the original CWA, and management is largely left to the states through the system of cooperative federalism.

3.3. State Tools

3.3.1. Clean Water Act Implementation

In most cases, states implement the CWA through a system of cooperative federalism, whereby the federal government, through the USEPA, oversees the implementation of federal law at the state level. States are free to set water quality standards and grant permits as long as their programs comply with the CWA and federal regulations. Because NPS pollution is not explicitly prohibited, USEPA cannot force states to eliminate NPS effluent. Instead, Section 208 of the CWA encourages state and local governments to voluntarily develop management plans to control it in exchange for federal funding [69]. Section 319 of the CWA requires states to identify water bodies that are impaired by NPS pollution and develop management and implementation plans that describe best management practices [65]. However, states are not required to penalize NPS polluters for failing to adopt best management practices, and states themselves are not subject to harsh penalties for failing to develop sound plans. Instead, Section 319 establishes economic incentives (e.g., cost-sharing) to encourage adoption of best management practices.

3.3.2. State laws: Florida's Coral Reef Protection Act

Coastal states may regulate activity in order to protect coral reefs. For example, ecosystem services provided to the state of Florida by its coral reefs include fishing, diving, boating, and tourism, which support the local economy, and to protect the coral reefs off the coast of Florida, the Florida legislature passed the Coral Reef Protection Act [70]. In addition to increasing public awareness of coral reef protection, the Act authorizes civil penalties for coral reef destruction and provides for the repair and mitigation of reef degradation. By levying fines upwards of $250,000 per infraction, the state of Florida established very strong disincentives for harming coral reefs by activities such as anchoring a vessel on a coral reef.

3.4. Local Government Tools

Common Law Tort Litigation

Common law, specifically tort law, defines the relationship between people and land at the level of the individual. Because the actions of individuals, taken together, have downstream impacts, we conclude our discussion of legal mechanisms with an analysis of recent shifts in common law to address and protect ecosystem services. Currently, there are no mechanisms in U.S. common law that require landowners to protect ecosystem structures and processes that generate critical ecosystem services [71]. Historically, common law encompassed an anti-wilderness, and therefore an anti-ecosystem services, bias [56]. In fact, U.S. courts actively interpreted the common law in a manner that favored the conversion of wilderness to "more productive" uses, such as agriculture and urban development [56]. This expansionist and environmentally destructive policy has long since outlived its usefulness, as societal priorities have shifted away from what were once considered positive outcomes and are now viewed as threats to biodiversity and ecosystem services.

Our understanding of the importance of ecosystem services and the manner in which biodiversity is critical to maintaining those services has improved with time but is still incomplete. Achieving sustainability is dependent upon ecosystem services that are part of ecological systems, and as it is currently interpreted, the common law is in conflict with this reality [56]. Private landowners have almost total discretion over natural resources on their land, coupled with no incentives to consider the social benefits or social costs of their activities. In order to address these market failures, ecosystem services research has been driven largely by a desire to estimate the social benefits or costs and internalize these externalities. Thus, perhaps this new understanding of ecosystem services will trigger a shift in the anti-ecosystem baseline in the common law [56].

For example, one area of common law—public nuisance—has begun to adapt to emerging knowledge associated with ecosystem services [56]. A recent Rhode Island trial court case found that the public was entitled to the ecosystem services (*i.e.*, filtration and cleaning of water) provided by a marsh owned by a private landowner and that by disturbing marshland, the owner was creating a public nuisance. Arguably, this case inserts ecosystem services into the public nuisance doctrine by asserting that the public benefit gained from ecosystem services outweigh the landowner's private property rights, and the landowner in the above case had no right to fill the marsh that provided these services [56].

4. Discussion

Sustainable systems are complex and characterized by links between ecological and social systems, and thus warrant special attention [72]. In this paper, we analyzed legal mechanisms for sustainable ecosystems, recognizing there are scale-dependent issues associated with the governance of these systems. Manifesting a transition to sustainability likely means that law will need to be integrated in a resilience-based governance framework [73]. Full integration, if even possible, may not be the universal solution, and such a transition requires research to better understand the complexity of social-ecological systems in order to inform the different mechanisms that could be used. Further, collaboration and communication are necessary in order to set sustainable limits and implement appropriate policy mechanisms (e.g., market mechanisms or other economic incentives) for meeting those targets. Because no panaceas exist for resilience-based governance [74], polycentric forms of governance, whereby no central authority has complete control and multiple levels of governance units exist at multiple scales [75], may be most appropriate for some social-ecological contexts, whereas other environmental contexts, such as point source pollutants, may be best addressed by a centralized authority (*i.e.*, role of the state in Clean Water Act implementation).

Using coral reefs as an example, we demonstrated how legal instruments could be used to manage for sustainability by protecting ecosystems and accommodating the transboundary nature of sustainability. Addressing issues from multiple spatial and temporal scales is necessary when dealing with such complexity. Systems can be managed to protect biodiversity, and therefore functional diversity and functional redundancy, buffering humans from the uncertainty in these complex systems. Doing so is the only way to account for resilience and, ultimately, move toward sustainability. Coral reefs, for example, are threatened by global, national, regional, and local threats. Our multi-scalar examination suggests existing legal mechanisms are not sufficiently integrated across scales to protect these fragile ecosystems and ensure we continue receiving the numerous ecosystem services coral reefs provide.

Climate change, overfishing, and pollution are primary threats to coral reefs, and all contribute individually or in combination to the loss of biodiversity in coral reef ecosystems. Unfortunately, there are no effective international laws currently in place that can address climate change, overfishing, and pollution. The LOS Convention deals with pollution and overfishing, but the United States has not ratified the treaty, and while the South Pacific Tuna Treaty deals with overfishing, it does so in a limited manner (*i.e.*, restricted to certain species and area). Thus, the biodiversity of U.S. coral reef ecosystems is dependent upon federal, state, and local laws for protection, which quite simply, are insufficient. For example, the combined state (3 miles from low water) and federal (from 3 to 12 miles) jurisdiction of waters, along with the Submerged Lands Act (12 to 24 miles) and the Exclusive Economic Zone (12 to 200 miles), does provide some capacity to manage coral reefs for resilience, as these laws allow for management of fishing and to a lesser extent pollution. However, these laws have little to no impact on climate change mitigation. While the National Marine Sanctuaries Act allows for no take zones, they are limited in scale. The Clean Water Act has done a good job at regulating point source water pollution but has limited capacity to regulate non-point source water pollution, which has a huge impact on water quality and is only managed via economic incentives from state governments. State laws to protect reefs, such as Florida's Coral Reef Protection Act (civil penalties for reef destruction) are good, but will likely not be effective in the face of threats to coral reef ecosystems that are global in nature (e.g., climate change) or stem from upstream or upland sources. These examples highlight the difficulty of protecting the biodiversity of coral reef ecosystems without coordinated multi-scalar laws and regulations.

In terms of resilience, high-level policy collaborations, like the National Ocean Council, show great promise for incorporating resilience concepts into ocean policy. A comprehensive, systems-based approach (*i.e.*, "Reef to Ridge") that includes terrestrial and transboundary environmental threats has high potential to further sustainability goals. These foundational steps in identifying barriers to managing for resilience, and research funding through the Coral Reef Conservation Act, could be actualized through new laws and legal reforms of existing laws at local, state, national, and international scales. Coupled with enforcement regimes that are either statutory, such as the Clean Water Act and National Marine Sanctuaries Act, or from common law, such as an expansion of the public trust doctrine to apply to marine resources, there is potential for a more sustainable future.

We assessed the law in a multi-scalar examination that illuminated the legal mechanisms that affect the resilience of coral reef ecosystems. There are many factors that can affect the resilience of ecosystems (e.g., perturbations), but we focused on biodiversity in this paper. In particular, we discussed the role of functional diversity and functional redundancy in contributing to the resilience of coral reef ecosystems. We assert that protecting species richness on reefs is not sufficient for system resilience. Rather, reefs should be managed for overall biodiversity, which will provide the best chance of maintaining essential diversity and redundancy of functions, response diversity, and keystone species. Further, reefs cannot be managed in isolation, as individual reefs cannot maintain system resilience. Large areas (e.g., marine protected areas) encompassing multiple coral reef systems are necessary for spatial resilience [32].

5. Conclusions

In order to achieve sustainability, we must develop new or adapt established policy to protect biological diversity. Such protection may guard against the loss of resilience, thereby protecting ecosystem services and providing a necessary component for sustainability. Ultimately, the problem is a global issue that requires a multi-pronged approach. Ecosystems are complicated, poorly understood systems and managing for resilience is further complicated by the spatial and temporal scales that must be considered and require multijurisdictional approaches. While we have conducted a multi-scalar legal examination of resilience and coral reefs, there is still much research needed to understand the effect of laws (that are largely compartmentalized) on cross-scale resilience and the multiple combinations and interactions such policy decisions can have.

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Author Contributions

Olivia Green, Ahjond Garmestani, Matt Hopton, and Matt Heberling each contributed equally to all sections of this paper. All authors read and approved the final manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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