Title: Underwater cultural heritage is integral to marine ecosystems

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Abstract (50/50 words): Underwater cultural heritage (UCH) supports marine biodiversity and influences connectivity. UCH structure, colonizing organisms, and anthropogenic stressors interact to shape sites over time, but these interactions are poorly understood. We express the urgent need for biology-archaeology collaborations to address interdisciplinary questions. We codify the emerging field of Maritime Heritage Ecology.

Main text (1608/1500 words):

Underwater cultural heritage role in the ecosystem

Underwater cultural heritage (UCH, see Glossary) constitutes the long-term remains of anthropogenic activities in the ocean. Shipwrecks, sunken aircraft, paleolithic middens, submerged settlements, and other artifacts are irreplaceable historical resources that also constitute habitats for microbes, flora, and fauna [1]. On a local scale, UCH provides the primary hard-bottom habitat and can be isolated and island-like. In places with a long history of seafaring and/or favorable conditions for preservation, such as the Mediterranean, UCH can be particularly abundant. UCH introduces novel ecosystem functions to the seafloor, including microbial communities [2,3] and obligate hard-bottom invertebrates and fish where there was previously only sand or mud [4].

The physical structure of UCH and the biological community inhabiting it undergo parallel changes over time (i.e., **site formation processes**). If exposed to a dynamic marine environment, wooden shipwrecks degrade quickly, leaving parts of the hull and a **ballast reef**. This process is influenced by shipworm colonization and closely parallels other organic matter-falls in the ocean. Limestone artifacts are particularly susceptible to bioerosion from a range of **boring species** [5]. Metal and fiberglass structures also degrade, but more slowly. Metal corrosion is strongly influenced by chemical conditions of the surrounding water and burial in sediment. Composite sites with multiple materials undergo complex transformations and heterogenous degradation. There is almost no understanding of how site formation processes and ecological **succession** influence one another, although understanding this **reciprocal influence** will be key for management of UCH sites and the biological communities inhabiting them (Figure 1).

UCH exhibits a **sphere of influence** on biodiversity beyond the physical bounds of its structure. In one case study, a shipwreck in the Line Islands caused a phase shift from a coral-dominated to a corallimorph-dominated community that persisted after the shipwreck was removed [6]. The *Costa Concordia* shipwreck in the Mediterranean similarly impacted the seafloor, causing regression of endemic habitats and a surge of opportunistic species (e.g., the bryozoan *Reteporella* sp.) [7]. Such far-reaching impacts of shipwrecks are likely mediated by the availability of trace metals such as copper and iron and the microbial biofilms that assimilate them [8]. However, interactions between UCH structure, microbial communities, and eukaryotic communities that drive **community assembly** are extremely poorly understood.

One key impact of UCH is on species distributions. By creating hard-bottom habitats where there was previously sand or mud, UCH can act as stepping-stones for **larval dispersal**. UCH in the western Atlantic hosts tropical fishes at the edge of their geographic ranges [9]. WWII shipwrecks in Brazil facilitated the spread of the invasive cup coral *Tubastraea coccinea* along that country's northern coast [10]. Such undesirable impacts of UCH present a challenge for management, which must balance historical preservation with ecological goals.

Like other marine habitats, UCH sites are impacted by anthropogenic stressors. Climate-related acidification, erosion, and intense storms accelerate the degradation of UCH. Fishing, especially bottom trawling, damages UCH and leads to the entanglement of ghost gear [11]. Eutrophication alters the community structure on otherwise similar shipwrecks [12]. The ecological disaster of the Deepwater Horizon oil spill altered microbial communities and accelerated corrosion of metal on historically-important shipwrecks in the Gulf of Mexico [13].

Research challenges

The dual objectives of protecting biodiversity and preserving cultural heritage necessitate a clear understanding of the processes impacting UCH sites and their biological communities. Managers in particular need to have a deep understanding and appreciation of UCH as historical and ecological resources. There is an urgent need for collaborative biology-archaeology research to fill knowledge gaps.

Recent years have seen a rise in studies on biological colonization of UCH, which is a promising trend. However, marine ecologists and maritime archaeologists rarely encounter one another in professional circles – they sit in different departments, attend different conferences, and publish in different journals. Furthermore, researchers are unlikely to take courses outside their home field beyond the undergraduate level. We have noticed an interest among biology and archaeology researchers in designing studies outside disciplinary boundaries, but a mutual ignorance of the vocabulary and research framework in each other's fields can lead to time-consuming diversions. Put succinctly, there is no need to re-invent the wheel when one can collaborate with the patent owner.

One challenge for biology-archaeology collaborations is the difference in cultural norms between fields, particularly surrounding study design. Research studies can take place at three theoretical levels. Low-level theory involves observations of the physical features, artifact assemblages, and/or biological communities at a given site. Mid-level theory includes generalizations that attempt to account for patterns between variables and among sites. High-level theory is a set of abstract rules that explain major phenomena.

Many archaeological studies constitute in-depth site descriptions (low-level theory). Descriptive studies may be ignored by ecologists, who place higher value on quantitative studies at the mid- and high- levels. Currently, a high-level theory for understanding UCH in an ecological context is lacking. Low- and mid- level studies constitute a valuable foundational database for the formation of high-level theory. Existing high-level ecological theories such as Island Biogeography Theory should be applied to UCH sites [14].

Framework for interdisciplinary research

Addressing these research challenges will require ecologists and archaeologists to work in strong interdisciplinary teams. Frequent, genuine dialogue and good-faith cooperation can mitigate cultural and training barriers. There is especially ripe opportunity for investigations of mid-level theory. For example, a study of UCH structure and community composition highlighted the value of shipwrecks as habitats and demonstrated the effects of fishing gear entanglement [15]. Likewise, there is a real opportunity for researchers and managers to bring knowledge of ecological succession and site formation processes (both mid-level theories) into policy considerations.

Here, we codify the emerging interdisciplinary field of **Maritime Heritage Ecology** by proposing a common vocabulary, framework, and identifying key overarching questions for collaborative study (Figure 1). Most of the examples provided in this review focus on shipwrecks because they are the best-studied UCH sites for ecological processes; however, the framework of Maritime Heritage Ecology can and should be applied to all UCH, including those in transitional environments, such as intertidal shipwrecks, wharfs, lighthouses, decommissioned oil rigs, and artifacts. It is our genuine hope that this framework will facilitate intentional interdisciplinary collaboration and address UCH management challenges.

Overarching question 1: How do site formation processes and succession influence one another?

UCH deterioration does not happen linearly. For shipwrecks, there is a wrecking event, which causes rapid change, followed by an **environmental equilibrium**. Shipwrecks that remain largely intact during wrecking (i.e., closed systems) degrade more slowly than open systems and present novel environmental conditions in the shipwreck interior. Simultaneously, **recruitment** of organisms to a UCH site depends on a suite of environmental and biological factors and may be stochastic. UCH structure undoubtedly influences the succession of microbes, flora, and fauna, but the reciprocal influence of UCH structure and biology over time has never been studied. How does the structure of UCH influence the species that colonize it, and how do those species influence the UCH structure in turn? How do subsequent **natural and cultural transformations** affect colonization by removing organisms from the community or revealing new surfaces for colonization? How do the time scales of ecological succession and site formation compare and interact?

<u>Overarching question 2: What is the net effect of UCH on biodiversity?</u>

As UCH becomes colonized and undergoes succession, the community may come to resemble a natural reef and host desirable species such as corals. UCH can also facilitate the spread of invasive species. Low-level studies on local and regional scales will be necessary to unravel the complex interactions of UCH structure and biodiversity. To what extent can UCH communities resemble natural reefs, and if so, how long does that process take? How can the efforts to preserve and restore natural reefs affect colonization and preservation of UCH? What are the long-term impacts of stepping-stone UCH sites on species distributions and larval dispersal/connectivity? How does the system change if these sites are removed or destroyed?

<u>Overarching question 3: How do anthropogenic stressors impact UCH structure and biological communities?</u>

Anthropogenic stressors range from micro-events such as SCUBA diving and fishing to macro-events including climate change, high-impact storm events, pollution, and ocean acidification. While the influence of rising temperatures and acidification on marine organisms has been extensively studied, understanding of these stressors on UCH structure and site formation processes is extremely limited. Anthropogenic stressors are overlaid and interact with other natural and cultural processes, but feedback cycles between these factors are poorly understood. On what time scales do different anthropogenic stressors impact UCH structure and communities? How does the spatial scale of a stressor control the extent or severity of impact? How can controls on human activities preserve historical and biological resources on UCH?

A path forward

In the Anthropocene, it is inappropriate to view anthropogenic structures as separate from naturally-occurring ecosystems and vice versa. Yet, this is the common view among many audiences and stakeholder groups. UCH constitutes integral and impactful seafloor habitats which influence biodiversity beyond the physical bounds of the site. Effective and genuine biology-archaeology collaborations are absolutely essential for future research. We have proposed a framework and questions for the emerging field of Maritime Heritage Ecology in order to launch interdisciplinary investigations. We call upon maritime archaeologists and marine ecologists alike to learn from one another and pursue answers to the broad-scale questions proposed here.

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Glossary (422/500 words):

Ballast reef: a reef formed by the remains of a ship's cargo or ballast rocks after the wooden hull has degraded and disappeared. It is the closest analogue of natural boulder reefs.

Community assembly: the process by which a biological community becomes established, including interactions among species and the structure of the habitat they occupy.

Cultural transformations (c-transforms): site formation process stemming from human activities and behaviors that modify archaeological sites over time including artifact removal, fishing damage, and litter.

Boring species: species that chemically and physically alter UCH to create cavities in the material, resulting in degradation or erosion. The best-known example is the shipworm *Teredo navalis,* but boring species span a wide taxonomic range, including cyanobacteria, fungi, algae, and invertebrates.

Environmental equilibrium: a state in which the slope of the rate of change for an underwater cultural heritage site is zero. This does not imply that the rate of change is zero – the site may still be changing, but at a constant rate.

Larval dispersal: the process by which the early life-history stages of invertebrates and fish spread through the marine environment, carried by oceanographic currents.

Maritime Heritage Ecology: an emerging interdisciplinary field of study integrating maritime archaeology, community ecology, and biological oceanography to understand how maritime heritage and underwater cultural heritage function as habitats.

Natural transformations (n-transforms): site formation processes stemming from environmental conditions such as wave action, chemical reactions, and biological colonization.

Reciprocal influence: the concept that the physical structure of a UCH site and the species that colonize it influence one another and together determine the transformations of the site over time.

Recruitment: the process of a larva transitioning from its pelagic to its benthic life-stage and establishing itself in a benthic community. Recruitment is defined as the survival of an individual until counted by a researcher.

Site formation processes: the causal mechanisms that move artifacts and structures from their use context to their archaeological context and lead to further transformations over time.

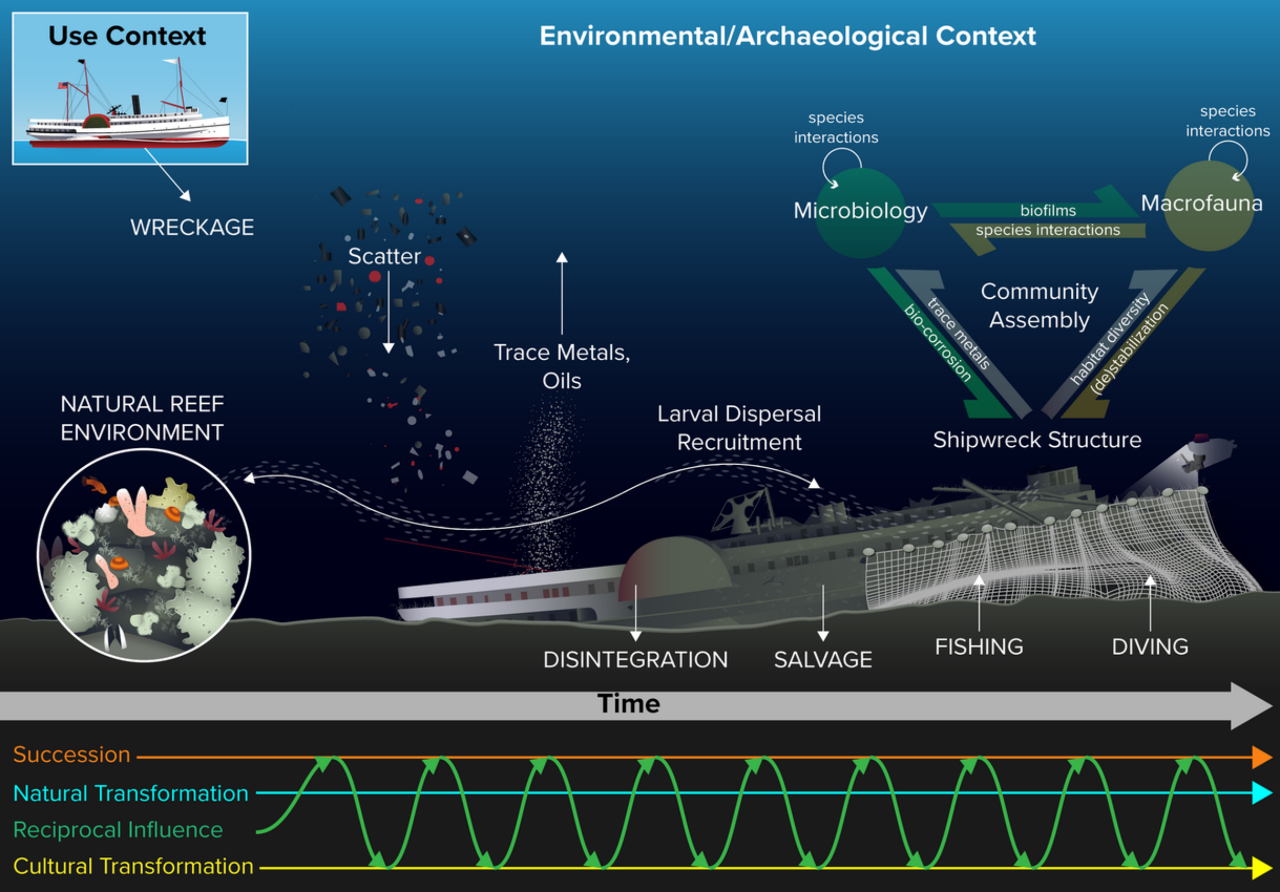
Sphere of influence: the three-dimensional space surrounding a UCH site with some observable impact on biodiversity. Examples include changes in species composition in the sediments and schools of reef fish or swarms of zooplankton in the water column.

Stabilizing species: species that have a net effect of preserving or preventing the erosion of UCH. The concept of a stabilizing species is largely theoretical, though some studies have suggested that metabolic by-products from certain species could preserve textiles or paper, and sessile reef-building invertebrates could shield artifacts from erosion.

Succession: the process of change in community structure over time as the result of environmental conditions or species interactions.

Underwater cultural heritage: the remains of sea-going vessels and anthropogenic activities in a submerged environment.

Figure 1: Intellectual framework for Maritime Heritage Ecology. A ship or other structure is transferred from its use context to its archaeological or environmental context via wrecking. Scattered materials, trace metals, and oil affect the surrounding environment. Disintegration and salvage remove material or contribute to the fragmentation of the shipwreck, but fishing and diving introduce material such as nets to the system. The UCH site is colonized by larval dispersal and recruitment of organisms from surrounding natural hard-bottom reefs and can serve as a stepping-stone for dispersal in turn. Interactions between microbes, macrofauna, and UCH structure shape the community. Succession of species, natural transformations, and cultural transformations of the site reciprocally influence one another over time.


Use Context
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WRECKAGE
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Microbiology
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species interactions
Macrofauna
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interactions
Community
Assembly
bio-corrosion
trace metals
habitat diversity
(de)stabilization
Shipwreck Structure
NATURAL REEF
ENVIRONMENT
Larval Dispersal
Recruitment
DISINTEGRATION
SALVAGE
FISHING
DIVING
Time
Succession
Natural Transformation
Reciprocal Influence
Cultural Transformation