

Airplanes and Microbes: Microbially-Influenced Corrosion of WWII Aluminum Aircraft Wrecks in the Pacific

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ABSTRACT

Aircraft were a major component of the U.S. war effort in the Pacific Theatre of WWII, and today numerous examples can be found throughout the waters of the Asia-Pacific region. Due to their cultural and historical significance to modern stakeholders, understanding the decay trajectories has become an important issue in the realm of archaeology and cultural heritage management. While the majority of corrosion studies have focused on electrochemical exchanges at the seawater-metal interface, far less attention has been paid to the effects of colonizing microorganisms (e.g. sulfate-reducing bacteria) that can contribute to increased rates of corrosion. Some studies of the microbiome of historic steel wrecks have been investigated in recent years, revealing a diverse mix of aerobic and anaerobic organisms. Yet, little has been done to understand the morphology and structure of the microbial community on aluminum aircraft in relation to corrosion processes. This paper summarizes the issues and previous efforts made in regards to microbially-influenced corrosion (MIC) of historical wrecks, while also outlining a proposed study that aims to investigate MIC of WWII aluminum aircraft in Saipan and Hawaii. It is the hope of the research team that the results will be used to better understand the decay trajectories of the aircraft and inform resource managers in their preservation practices. Field work and laboratory analysis are scheduled to take place in the spring and summer of 2020, with financial support being provided by a National Center for Preservation Technology and Training grant from the National Park Service. The project represents a collaboration between archaeologists and microbiologists in a concerted effort to confront historical preservation issues with an interdisciplinary approach. Finally, this paper concludes with a discussion on the importance of a public archaeology focus and how this project will include the local community throughout our time in the field.

Key words: Corrosion, World War II, Aluminum, Microbiology

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INTRODUCTION

For many, the narrative of World War II (WWII) in Hawai'i centers on two key moments: the Attack on Pearl Harbor and the Battle of Midway. The tendency to concentrate on these two events comes at the expense for an appreciation of the role the islands played in preparing United States (U.S.) servicemembers for the Western Pacific. Hawai'i, which hosted an estimated two million servicemembers throughout the war's duration (Chapman, 2014: 54), offered the ideal training location for troops who were deployed as a part of the Allied island-hopping campaign.

While the shores and forests provided space for amphibious assault and jungle warfare training, the Hawaiian skies served as the backdrop for thousands of flight hours. Airmen practiced crucial skills, such as carrier operations and aerial bombing, which made use of offshore geological targets, such as the island of Kaho'olawe. Although military training during WWII was an inherently dangerous exercise, regardless of focus, aviation training unquestionably posed the largest risk. Within the continental U.S. alone, 21,583 planes were lost, resulting in a total of 14,903 aviator fatalities (U.S. Army Office of Statistical Control, 1945: 185, 309). To put this in perspective, that loss is higher than the U.S. death totals for all wars prior to the American Civil War, combined. According to the Naval History and Heritage Command (NHHC), an estimated 1,124 naval planes sunk in Hawaiian waters, the majority of which were training incidents (NOAA Maritime Heritage Program, 2017:115). The total for U.S. Army aircraft is presumed to be at least half of the naval totals (Gen. Leaf, pers. comm., 2021) These incidents have left an indelible impact on the Hawaiian seascape.

Today, wrecked aircraft constitute a major portion of Hawai'i's underwater cultural heritage (UCH), and play an important role in the islands' diving tourism industry. Many of these aircraft are protected by, or at least eligible for legal protection under, the Sunken Military Craft Act (2004) and the National Historical Preservation Act (1966). However, the vessels' face numerous, environmental preservation threats, namely corrosion, which remain impervious to legal mandates. Thus, successful preservation will be predicated on the ability to mitigate the effects of ungovernable natural processes.

In hopes of contributing to the understanding of the specific risks that submerged historic aircraft encounter, this paper focuses on microbiologically-influenced corrosion (MIC) and the first study to collect in situ microbial samples from the surfaces of WWII plane wrecks. The following discussion of MIC and its relation to UCH is used to frame a Hawai'i -based project, for which fieldwork was completed in April and August 2021. The project is led by an interdisciplinary team from East Carolina University consisting of archaeologists and biologists. It was made possible by a 2019 National Center for Preservation Technology and Training grant from the U.S. National Park Service. This research aims to elucidate information on the microbial community associated with submerged WWII aircraft and how this information can assist with sustainable site management.

MICROBIOLOGICALLY-INFLUENCED CORROSION (MIC)

The field of archaeology has increasingly recognized the value of in situ preservation. One way researchers can make an immediate and valuable contribution to efforts that increase the effectiveness of this management strategy is by understanding the environmental factors that may compromise preservation. Among these forces, as it pertains to the survival of metallic underwater cultural heritage, corrosion has rightfully garnered the most attention. A multitude of studies (e.g. MacLeod 2006; 2016) have assessed how the marine environment, through generalized corrosion, negatively impacts the physical status of shipwrecks and wrecked aircraft sites.

However, there is rarely explicit attention paid to the non-deterministic forms of corrosion, namely microbiologically influenced corrosion (MIC) (Moore, 2015). MIC refers to the ability of microorganisms to influence corrosion processes of an object by altering the electrochemical conditions of the microenvironment (Little and Lee, 2008). The nonlinear direction of MIC is owed to the dynamic nature of microbial communities and the tendency for these communities to vary spatially. Within a marine setting, microenvironmental conditions such as oxygen content, light availability, and substrate metallurgy, contribute to this variation.

While certain anaerobic microbes (e.g. Sulfate-Reducing Bacteria) in marine environments are frequently credited as being culprits, MIC almost always requires a diverse and complex microbial community (Little and Wagner, 1997). These communities exist within slimy layers of biofilm, which contain the requisite oxygen gradients and taxonomic relationships that enable MIC. While yet to be studied in the context of an aluminum-based wreck, this form of corrosion has been the subject of numerous projects focused on the microbiomes associated with historic iron shipwrecks (Albahri et al., 2019; Little et al., 2019; Mugge et al., 2019; Price et al. 2020; Salazar and Little, 2017).

Microbiologically influenced corrosion is especially relevant to submerged aircraft, given the way aluminum corrodes in seawater. Unlike iron-based shipwrecks, aluminum develops a protective oxide barrier (Al_2O_3) when submerged. This prevents the electron exchange associated with corrosive redox reactions (Davis, 1999). However, the presence of biofilm and the associated microbial activity can work to disrupt and limit the effectiveness of the oxide barrier through one of two ways. The first is known as a differential aeration cell, where the deoxygenated environment created within and under biofilm prompts increased metal dissolution through redox reactions (Little and Lee, 2008).

The second MIC pathway relies on ecological relationships between clades of microbes (Emerson, 2018). In this instance, the organic waste products of aerobic microbes found in the outer, more oxygenated sections of the biofilm layer serve as the terminal electron donor used in the metabolic activities of anaerobic microbes found in the deoxygenated areas of the biofilm (Ghali, 2010). The resulting metabolites, which can include hydrogen sulfide and methane, react with the underlying metal substrate and prompt further dissolution (Guan et al., 2017). MIC is likely to manifest itself visually as pits and perforations along the surface of an aluminum wreck. This threatens the structural integrity of the aircraft, which can lead to disarticulation and the loss of a site's recognizability. The latter is one of the primary contributors to the ability of WWII plane wrecks to attract a wide range of site users, who otherwise may not appreciate an amorphous metallic mass (MacLeod and Harvey, 2014).

STUDY SITES

A total of four sites were chosen for this study, with two off the coast of southern Maui and two off the coast of eastern O'ahu (Figure 1). The Maui aircraft, both located within Mā'alaea Bay, included a Curtiss SB2C-1C Helldiver (Bureau Number 18400; U.S. Navy Bombing Squadron 4) and Grumman F6F-3 Hellcat. The Hellcat is 600 meters (m) offshore, while the Helldiver, 4.5 kilometers (km) to the northwest, is around 1km from the shoreline. Both wrecks are situated on sandy seafloors with relatively little exposure to wave energy. The Hellcat, with a depth of 10.5m is surrounded by seagrass beds, which dissipate as one moves away from the wreck. While the deeper Helldiver site, at 16.5m, lacks the subaquatic vegetation, like the Hellcat, it acts as an artificial reef. Both sites support a wide array of fish and invertebrate species, operating as an oasis of sorts.

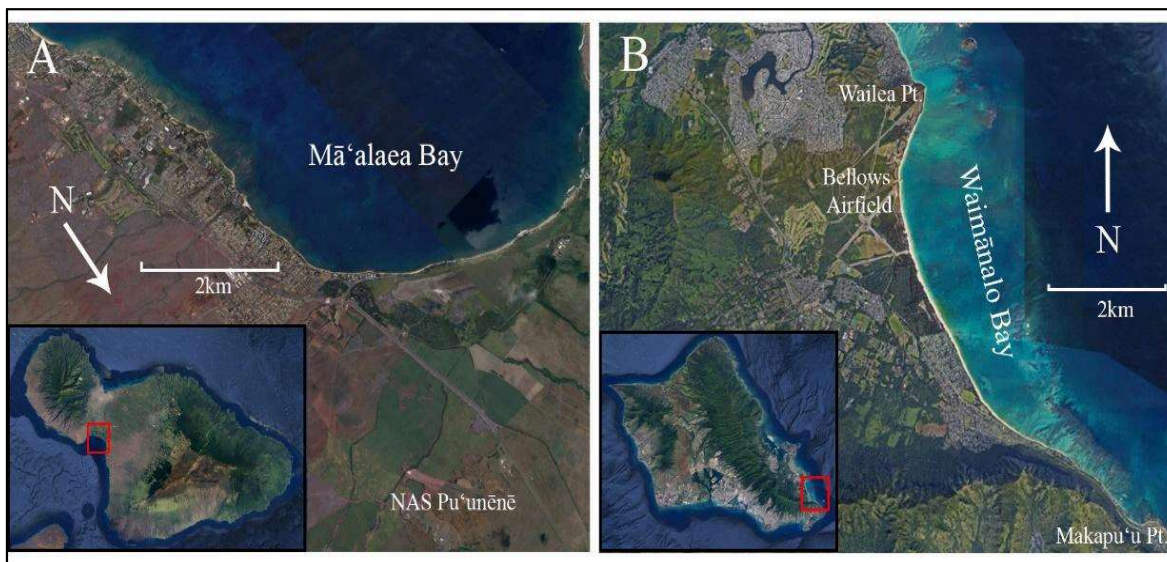


Figure 1: Map of Study Areas (Google Earth)

On August 31, 1944, Lieutenant William E. Dill and radioman Kenneth W. Jobe were conducting a dive bomb run in their Curtiss SB2C-1C Helldiver launched from Naval Air Station (NAS) Pu'unēnē (NOAA ONMS, 2011). While ascending out of a dive, a twist in the plane's tail assembly caused the rudder controls to malfunction. Lieutenant Dill recognized that he no longer had sufficient command over the aircraft, and that a return to Pu'unēnē was impossible. He safely crash-landed the bomber in Mā'alaea Bay, where he and his radioman were later rescued. The U.S. Navy never recovered the Helldiver, and over time, its location was forgotten.

It was not until 2010, when Maui dive operator Brad Varney located the aircraft after a tip from local fishermen (Maui Dreams Dive Co., 2013). Almost immediately after Mr. Varney dove on the Helldiver for the first time, local interest in the subject exploded. A boat captain for another dive company made the startling discovery that the aircraft's Bureau Number (BuNo) could still be read on the detached vertical stabilizer (Maui Dreams Dive Co., 2013). Matching the BuNo (18400) with the NHHC's crash records led to the realization that the plane is the same one ditched by Lieutenant Dill in 1944. The wreck is noted for its near completeness, with the rescue raft as the only notable missing part. The vertical stabilizer was detached from the tail and is mostly buried near the aft end of the aircraft. The wreck is heavily encrusted with coral (mainly on the fuselage) and remains upright of the seafloor.

Far less is known about the history of the Hellcat. Given the proximity of the wreck to NAS Pu'unēnē, it is not unreasonable to think that this plane also crashed after a takeoff or prior to landing. In 1983, the Hellcat was located by longtime recreational diver and Maui resident Roger Pannier (Uechi, 2017). Interest in the wreck, outside of the diving community, appeared minimal until the 2011 Maui Maritime Heritage Resources Survey. Project participants mapped and photographed the wreck, which allowed researchers to make inferences about the identity of the plane. While not benefited by the presence of a BuNo, those leading the survey concluded that the landing gear configuration and engine exhaust flaps drew favorable comparisons to the F6F-3 model of Hellcat (NOAA ONMS, 2011). The site's nearshore location make it particularly desirable for scooter-assisted divers who launch from shore, as accessing this site does not require a boat. While not as intact as the Helldiver, portions of the aircraft's fuselage and wings are still present. An associated radial engine and propeller remain intact, though they are nearly 23m away.

The O‘ahu aircraft consist of a single wing from an unidentified Vought F4U Corsair and a Republic P-47D-21-RA Thunderbolt (Serial Number 43-25601; U.S. Army 45th Fighter Squadron). The sites, separated by Waimānalo Bay, are each located off headlands (Wailea and Makapu‘u Points). Beyond differing in terms of depth, the Corsair wing at 11m and the Thunderbolt at only 4m, the aircraft lie within vastly different environments. Unlike the Corsair wing, which is situated on a sandy section of seafloor, the Thunderbolt is firmly entrenched on a reef. Like the Maui sites, each of these wrecks is associated with a high level of reef fish diversity and serves as a substrate for numerous invertebrates.

The identity of the Thunderbolt was achieved through archival research by Pomey (2008). According to the accident report, the aircraft wrecked on June 21, 1944 shortly after takeoff. Lieutenant William H. Sparks was beginning a practice Very Long-Range flight, when a mechanical failure forced Sparks to ditch his fighter 1000 yards off the end of the runway at Bellows Airfield. The pilot was able to safely eject, though the plane was deemed unrecoverable. It was, however, stripped of salvageable parts, such as the gages and machine guns. Today, a section of the fuselage, cockpit, and wings remain intact. The plane lies upright on the reef and at a slight upward angle as one moves towards the aft end. It is listing to one side, so that the left wing is partially buried, while the right wing extrudes into the water column. There is a small debris field associated with this section of the wreck, which includes the frames of the fuselage’s aft end. The engine, engine cowlings, and propeller can be found 7.5m from the main body of the wreck. The site’s shallow depth and accessibility via kayak make it a popular snorkeling spot.

By contrast, the Corsair wing receives very little attention from the recreational diving and snorkeling community. Beyond it only being a fragment of a plane, its location in an otherwise barren area and the tendency to be subjected to dangerously strong currents and swells deter visitors. The wing is also known to be buried seasonally. These factors make the site an ideal comparison with those previously described (Figure 2), with special attention paid to the potential impact human interactions and sediment movement have on the microbial community.

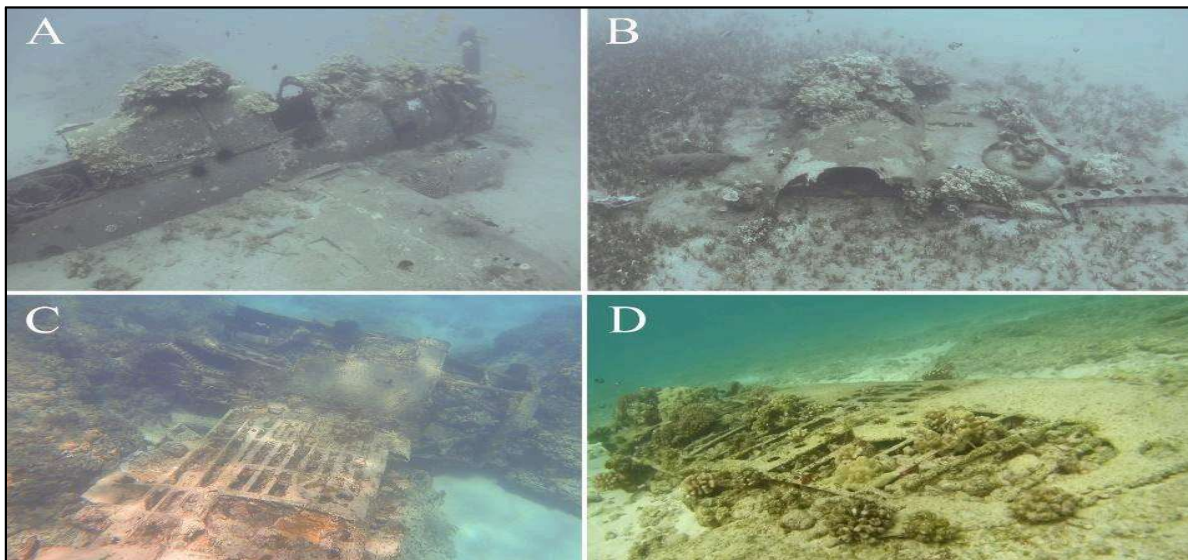


Figure 2: Site Photos: A. Helldiver (J. Raupp); B. Hellcat (J. Raupp), C. Thunderbolt (D. Bush); D. Corsair Wing (A. Kordish)

METHODOLOGY

Foundational in nature, this study sought to collect baseline data on the taxonomic composition of each wreck's microbiome in hopes of discerning spatial associations between microbial communities and areas of visible corrosion. To accomplish this, divers collected biofilm from 10-centimeter x 10-centimeter (cm) sampling areas on aluminum surfaces of all four aircraft (Figure 3). Sampling locations were divided evenly between visibly-corroded areas (Figure 4) and areas absent of corrosion. Researchers also collected sediment and water samples for the purposes of understanding how the wrecks' microbiomes may be affected by that of the surrounding environment and vice versa. The water samples' biological material was captured using 0.2 micrometer (μm) Polyethersulfone (PES) filters. Finally, incremental water temperatures and dissolved oxygen readings were taken at each site.

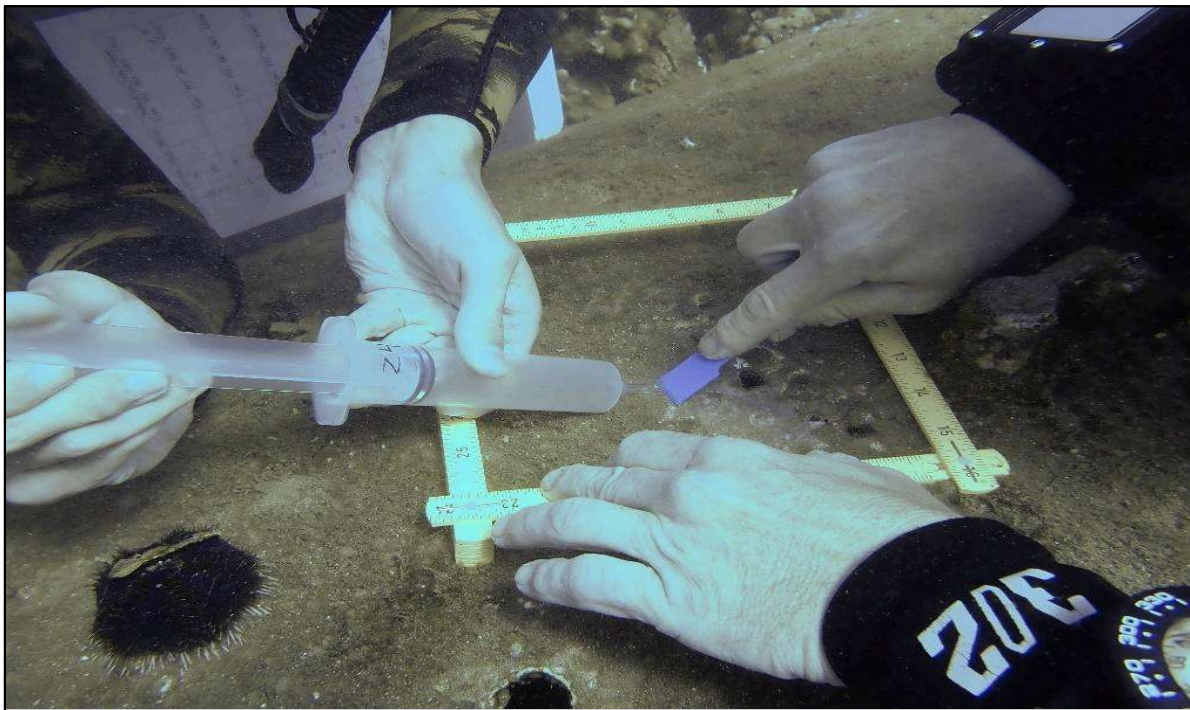


Figure 3. Biofilm collection at Maui Hellcat. (J. McKinnon).

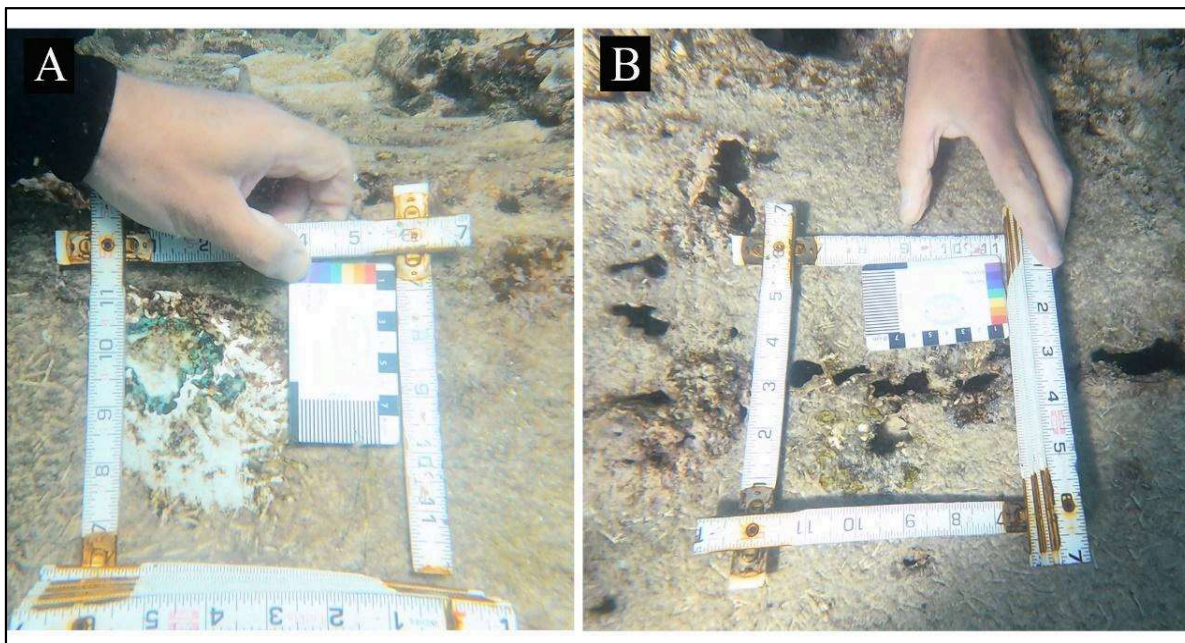


Figure 4: Examples of corroded aircraft surfaces on Thunderbolt. Note the blue-green color and pitting. (D. Bush)

All samples were shipped on ice to East Carolina University for DNA extractions (Figure 5). Thus far, only the Maui samples have been processed, with the isolated genetic material being shipped to the Integrated Microbiome Resource (IMR) sequencing center in Halifax, Nova Scotia. The Oahu samples are expected to be processed and sequenced within the coming months. IMR uses an Illumina MiSeq sequencer, which produces millions of reads per run on a small, targeted region of DNA. This provides greater coverage from the perspective of community-level statistics and make it a suitable choice for this project (Quail et al., 2012). Sequencing will target the V4-V5 region of the 16S rRNA gene. This gene is chosen due to its ubiquity in bacteria and often diagnostic nature, as result of it being well-conserved and slow evolving (Schmalenberger et al., 2001).

RESULTS

Although some of the Maui sample extractions needed to be repeated, all final DNA yields surpassed the 1 ng/μL threshold needed for sequencing. Of the 20 biofilm samples taken from aluminum surfaces (10 from each site), 19 of them were successfully sequenced. While, all water filter samples (3 from each site) were successful, 4 of the 10 sediment samples (5 from each site) failed during the sequencing step, perhaps the result of PCR amplification inhibition. The failed Maui samples will be re-processed and sequenced alongside the O‘ahu samples.

Currently, the Maui sequencing data is being translated into taxonomic information using the software program Mothur v.1.39.5. The information will then be evaluated using the open-source statistics program R to explore the dataset’s variation through multivariate methods. While several statistical tools are available, non-metric dimensional scaling (NMDS) models have proven particularly adept at highlighting potential taxonomic and spatial associations (Oksanen, 2011). Rather than being focused solely on a single metric, such as relative abundance, this study is more concerned with how ecological relationships amongst clades of microbes may contribute the composition and diversity of the wrecks’ microbiomes. Of the greatest interest, is how might the

microbial communities on and directly adjacent to areas of visible corrosion differ from those associated with non-corroded locations. With this information serving as a baseline, it may be possible to further expand this research in hopes of establishing patterns that can be used to predict microbiologically-influenced corrosion of submerged aircraft wrecks.

DISCUSSION

This project comes in the wake of the United Nations' 2017 declaration that 2021-2030 will be the "Decade of Ocean Science for Sustainable Development" (the Decade). This initiative emphasized the need to "enhance the opportunities and equitable access to economic benefits arising from marine resources and technology," (UNESCO, 2018:39). The Decades' Revised Roadmap only mentions UCH once (UNESCO 2018:18), despite the obvious potential for submerged archaeological sites to act as a resource for sustainable economic growth, largely through the heritage and dive tourism industries. This is particularly true in the Asia-Pacific region, including Hawai'i, where vestiges of war are strewn throughout the area's waters.

Takadas et al. (2019) viewed this omission as both a challenge and opportunity for maritime archaeologists to better situate the discipline within the broader conception of marine sciences. There is a need to approach historic preservation from a more scientifically grounded perspective that considers long-term sustainability and site formation. This study seeks to fulfill such a desire, with the potential results serving as a baseline for spatial and longitudinal comparisons that assess changes in microbiome diversity associated with submerged aircraft wrecks.

Furthermore, this project is intended to provide a viable methodology for site managers interested in monitoring the microbial communities associated with UCH sites. This not only has the effect of fostering sustainable coastal resource management, but collaboration and the transfer of knowledge can shift site stewardship from off-island researchers to local communities. By understanding the preservation threats, UCH sites can be more effectively protected, ensuring their survival and benefits for all stakeholders.

Eventually, mitigations strategies aimed at curbing the effects of MIC may be formulated based on these sorts of studies. Potential solutions include naturally produced biocides, or other organic (isothiazolone, quaternary ammonium, and aldehydes) and inorganic (e.g. ozone, chlorine, and bromine), which compounds have proven capable of reducing biofouling and microbial cell activity (Lee et al., 2010). Alternatively, promoting the growth of corrosion-inhibiting microorganisms, or preventing the establishment of biofilm through the application of D-amino acids may serve as other forms of mitigation (Nelson et al., 2017). The development of preservation strategies will need to be complimented by ecological research aimed at ensuring treatments do not have an adverse effect on other aspects of the natural environment, especially as it relates to economically valuable fish.

The field of UCH management, however, is still years away from this step of in situ preservation of WWII aircraft wrecks. For now, managers and researchers can concentrate efforts in better understanding the associations between microbial diversity and active corrosion of wreck sites, as advocated in this project. Collaborations between archaeologists and microbiologists, such as this project, can assist with revealing information on the synergistic microbial relationships that enable MIC and how community structure further influences corrosion.

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Biography



Born and raised in Kailua, Oahu, Dominic Bush is currently a PhD candidate at East Carolina University's Coastal Resource Management Program and hold degrees in anthropology from the University of Notre Dame (BA '16) and Washington State University (MA '18). He is passionate about the discovery, documentation, and preservation of underwater archaeological sites, particularly those related to World War II in the Pacific. Dominic hopes to use a multi-disciplinary approach, combined with indigenous collaboration, to ensure sites are protected and enjoyed by many.